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FIELD EVALUATION OF A UTILITY DRY SCRUBBING SYSTEM

by

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16. ABSTRACT The report gives results of the first independent evaluation of a full-scale utility spray-dryer/baghouse dry flue gas desulfurization (FGD) system. The system treats flue gas from a nominal 100 MW of coal-fired power generation. The test program, conducted during July-October 1983, used two different coals as boiler fuels: one, a subbituminous coal and coke mixture with a nominal 1.2 percent sulfur content; and the other, a 3.4 percent sulfur Illinois bituminous coal. SO2 removal, particulate emissions, sulfuric acid removal, and extensive process data were recorded. Low sulfur coal tests indicated that 75 percent SO2 removal was achievable in the short term at reagent ratios of 0.6 to 0.7, and 90 percent SO2 removal was achievable at a reagent ratio of about 0.8. An average removal of nearly 90 percent was achieved in short-term tests with high sulfur coal at reagent ratios of 1.3 to 1.4. Calcium chloride addition to the atomizer feed slurry was found to reduce the lime addition requirements for high sulfur tests by about 25 percent.

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ABSTRACT

This program, co-funded by the U.S. Environmental Protection Agency and the Electric Power Research Institute, has resulted in an evaluation of a full-scale utility spray dryer/baghouse dry FGD system. The system is installed at the Northern States Power Company's Riverside Station and treats flue gas from a nominal 100 MW of coal-fired power generation. This has been the first independent evaluation of a full-scale spray dryer/baghouse system.

For the test program, two different coals were used as boiler fuels. One coal was a subbituminous coal and coke mixture with a nominal 1.2 percent sulfur content. The second was a 3.4 percent sulfur Illinois bituminous coal.

The test program was conducted from July to October 1983. SO_2 removal, particulate emissions, sulfuric acid removal and extensive process data were recorded. Low sulfur coal tests indicated that 75 percent SO_2 removal was achievable in the short term at reagent ratios of 0.6 to 0.7, and 90 percent SO_2 removal was achievable at a reagent ratio of about 0.8. An average removal of nearly 90 percent was achieved in short-term tests with high sulfur coal at reagent ratios of 1.3 to 1.4. Calcium chloride addition to the atomizer feed slurry was found to reduce the lime addition requirements for high sulfur tests by approximately 25 percent.

TABLE OF CONTENTS

Page

Abstract.. iii

List of Figures.. ix

List of Tables... xii

Acknowledgements... xvi

Section

1 INTRODUCTION.. 1-1

1.1 Background.. 1-1
1.2 Project Description................................... 1-2
1.3 Report Organization................................... 1-4

2 SUMMARY AND CONCLUSIONS................................. 2-1

2.1 Summary... 2-1
2.1.1 System Operation.................................... 2-1
2.1.2 SO_2 Removal and Lime Reagent Consumption Performance.. 2-2
2.1.3 Removal of Flue Gas Sulfuric Acid Content........... 2-3
2.1.4 Particulate Removal................................. 2-4
2.1.5 Power Consumption................................... 2-5
2.1.6 Waste Solids Disposal Characteristics............... 2-5
2.2 Conclusions... 2-6
2.2.1 System Operation.................................... 2-6
2.2.2 SO_2 Removal Performance and Lime Reagent Consumption... 2-7
2.2.3 Particulate Removal................................. 2-8
2.2.4 Waste Disposal Characteristics...................... 2-9
2.3 References.. 2-9

3 RECOMMENDATIONS... 3-1

4 SYSTEM DESCRIPTION...................................... 4-1

4.1 Test Site... 4-1
4.2 Overall Flow Scheme................................... 4-2
4.3 Process Subsystems.................................... 4-4
4.3.1 Spray Dryer/Atomizer................................ 4-4
4.3.2 Fabric Filter....................................... 4-5
4.3.3 Reagent Preparation................................. 4-6
4.3.4 Atomizer Feed Preparation........................... 4-8
4.3.5 Solids Handling..................................... 4-10
4.3.6 Process Control..................................... 4-11

TABLE OF CONTENTS (Continued)

Section Page

5 TEST PROGRAM DESCRIPTION.................................. 5-1

5.1 Test Plan.. 5-1
5.2 System Modifications................................... 5-5
5.2.1 Continuous Emissions Monitoring System (CEMS)... 5-8
5.2.2 SO_2 Removal Control Software................ 5-13
5.3 System Limitations..................................... 5-14
5.4 References... 5-19

6 SYSTEM OPERATION.. 6-1
6.1 System Operation Overview.............................. 6-2
6.2 Discussion of Operating Problems....................... 6-8
6.2.1 Slurry Feed System............................... 6-8
6.2.2 Ash Handling System.............................. 6-9
6.2.3 Ball Mill Slaker................................. 6-12
6.2.4 Atomizer Problems................................ 6-14
6.3 References... 6-16

7 EMISSION CONTROL PERFORMANCE.............................. 7-1

7.1 SO_2 Removal Performance............................. 7-1
7.1.1 SO_2 Removal During Low Sulfur Operation..... 7-2
7.1.2 High Sulfur SO_2 Removal Results............. 7-25
7.2 Gas Phase Sulfuric Acid Removal Results................ 7-46
7.3 Particulate Removal Results............................ 7-50
7.4 Comparison of Current Results with Previous Joy/Niro Results at Riverside.................................... 7-58
7.5 References... 7-64

8 PROCESS REQUIREMENTS...................................... 8-1

8.1 Raw Material Requirements.............................. 8-1
8.2 Utility Requirements................................... 8-3
8.3 References... 8-6

9 WASTE PRODUCT CHARACTERIZATION............................ 9-1

9.1 Descriptions of Samples and Test Procedures............ 9-2
9.1.1 Sample Descriptions.............................. 9-2
9.1.2 Test Procedures.................................. 9-4
9.2 Waste Solids Chemical Analyses......................... 9-6
9.2.1 Elemental Concentrations in Waste Solids........ 9-6
9.2.2 Anionic Species in Solids as Measured by Wet Chemical Procedures............................ 9-8
9.2.3 Moisture Content and Insoluble Fraction of Waste Solids.. 9-12
9.3 Waste Particle Morphology.............................. 9-12
9.4 Physical Properties of Compacted and Cured Wastes...... 9-20

TABLE OF CONTENTS (Continued)

Section Page

9.4.1 Strength Development 9-20
9.4.2 Permeability 9-25
9.5 Waste Solids Leachate Properties 9-26
9.5.1 Description of Extraction Procedures 9-28
9.5.2 Elemental Concentrations in Extracts 9-30
9.5.3 Anionic Species Concentrations in Neutral Extracts 9-37
9.5.4 Results of Other Water Quality Measurements on Neutral Extracts 9-42
9.6 Comparison of Waste Product Characterization With Results of Previous Studies 9-44
9.7 References 9-46

APPENDIX A Sampling and Analytical Procedures A-1
A-1 Sampling and Analytical Procedures Used During the On-Site Test Program A-2
A.1 Site Description A-3
A.2 CEMS Certification and Monitoring A-3
A.2.1 CEMS Description A-10
A.2.2 Certification Procedures A-13
A.2.3 CEMS Monitoring A-15
A.3 Flue Gas Sampling and Analysis Procedures A-16
A.3.1 Flue Gas Moisture Determination A-17
A.3.2 Flue Gas Molecular Weight Determination A-17
A.3.3 Flue Gas SO_2 Determinations A-17
A.3.4 Volumetric Gas Flow Rate Determination A-20
A.3.5 Particulate Grainloading Determinations A-20
A.3.6 Flue Gas SO_3/H_2OSO_4 Determination A-22
A.4 Process Sample Collection and Analysis A-28
A.4.1 Sample Collection A-28
A.4.2 Sample Analysis A-29
A.5 References A-34
A-2 Experimental Techniques A-35

APPENDIX B Coal Analyses B-1

APPENDIX C Conversion Factors C-1

APPENDIX D DATA QUALITY D-1

D.1 QC Data D-1
D.1.1 QC Efforts for the CEMS D-2
D.1.2 QC Efforts for Analytical Measurements D-14
D.2 QA Audit Results D-18
D.2.1 Continuous Emission Monitors D-20
D.2.2 Method 6 SO_2 Determinations D-20

TABLE OF CONTENTS (Continued)

Section		Page
	D.2.3 Calcium Analyses	D-25
	D.2.4 Orsat Analyses	D-25
	D.2.5 Dry Gas Meters	D-25
	D.2.6 Balances	D-28
	D.2.7 ASTM Temperature Rise	D-28
	D.2.8 Systems Audit	D-28
APPENDIX E	ADDITIONAL WASTE SOLIDS CHARACTERIZATION ANALYSES	E-1
APPENDIX F	JOY/NIRO COMMENTS	F-1

LIST OF FIGURES

Figure — Page

4-1 Overall Flow Diagram for the Riverside Dry FGD System....... 4-3

4-2 Schematic of the Reagent Preparation System................. 4-7

4-3 Schematic of the Atomizer Feed Preparation System........... 4-9

5-1 Top View of Riverside Dry FGD System Duct Work Showing CEM System Installation.................................... 5-10

5-2 Schematic of Continuous Emission Monitor System............ 5-11

5-3 Illustration of Planned Boiler Operation During Test Program 5-16

6-1 Simplified Cross Section of Ball Mill Slaker................ 6-13

7-1 Trend Plot of Major System Parameters During One Week of Low Sulfur Coal Operation.................................... 7-19

7-2 Trend Plot of Major System Parameters During One Week of Low Sulfur Coal Operation, Edited to Show Only Data Used in Test Averages.. 7-24

7-3 Trend Plot of Major System Parameters During One Week of High Sulfur Coal Operation.................................... 7-35

7-4 Trend Plot of Major System Parameters During One Week of High Sulfur Coal Operation, Edited to Show Only Data Used in Test Averages.. 7-39

9-1 Scanning Electron Micrographs of Spray Dryer Product From the Baghouse During Low Sulfur Coal Run (75% Removal) at Riverside Station.. 9-14

9-2 Scanning Electron Micrograph and Elemental Scans of Spray Dryer Product From the Baghouse During Low Sulfur Coal Test (75% Removal) at Riverside Station......................... 9-16

9-3 Scanning Electron Micrographs of Spray Dryer Product from the Baghouse During High Sulfur Coal Baseline Test (90% Removal) at Riverside Station.............................. 9-17

9-4 Scanning Electron Micrographs of Spray Dryer Product from the Baghouse During High Sulfur Coal Baseline Test (90% Removal) at Riverside Station.................................... 9-18

9-5 Elemental Scan of Surface of Spray Dryer Product from the Baghouse During High Sulfur Coal Baseline Test (90% Removal) at the Riverside Station................................ 9-19

LIST OF FIGURES (Continued)

Figure **Page**

9-6 Scanning Electron Micrographs of Spray Dryer Product from the Baghouse During High Sulfur Coal Test with $CaCl_2$ Addition (90% Removal) at Riverside Station.......................... 9-21

9-7 Elemental Scan of Surface of Spray Dryer Product from the Baghouse During High Sulfur Coal Chloride Addition Test (90% Removal) at Riverside Station.......................... 9-22

A-1 Sketch of Riverside Generation Station...................... A-4

A-2 Solid, Liquid, and Slurry Sample Locations on Dry Scrubbing System at Riverside Generation Station...................... A-5

A-3 Top View of Duct Work At NSP Riverside Station Illustrating Flue Gas Sampling Locations................................ A-6

A-4 Schematic of the CEMS Used on the Dry SO_2 Scrubber System at Riverside.. A-11

A-5 Schematic of Lear Siegler In-stack Monitor.................. A-12

A-6 EPA Method 6 SO_2 Sampling Train............................ A-19

A-7 EPA-17 In-Stack Total Particulate Sampling Train............ A-21

A-8 SO_2-SO_3/H_2SO_4 Sampling Train............................ A-23

A-9 Pyrex Thimble Holder.. A-25

A-10 Glass Wool SO_3/H_2SO_4 Condenser............................ A-27

D-1 CEMS Variability Data, Low Sulfur Coal Inlet DuPont SO_2 QC Gas................................ D-8

D-2 CEMS Variability Data, Low Sulfur Coal Inlet Thermox QC O_2 Gas................................ D-8

D-3 CEMS Variability Data, Low Sulfur Coal Lear-Siegler SO_2 QC Gas............................. D-9

D-4 CEMS Variability Data, Low Sulfur Coal Outlet Thermox O_2 QC Gas............................... D-9

D-5 CEMS Variability Data, High Sulfur Coal Inlet DuPont SO_2 QC Gas................................ D-10

D-6 CEMS Variability Data, High Sulfur Coal Inlet Thermox QC Gas.................................. D-10

LIST OF FIGURES (Continued)

Figure		Page
D-7	CEMS Variability Data, High Sulfur Coal Lear-Seigler QC Gas	D-11
D-8	CEMS Variability Data, High Sulfur Coal Outlet Thermox QC Gas	D-11
D-9	Quality Control Chart Repeat Sample Analyses for Calcium	D-14
D-10	Quality Control Chart Repeat Sample Analyses for Sulfate	D-14

LIST OF TABLES

Table		Page
4-1	Key Process Control Measurements	4-12
5-1	Original Test Plan for the Riverside Spray Dryer/Baghouse Characterization	5-2
5-2	Revised Test Schedule for the Riverside Spray Dryer/Baghouse Characterization	5-6
5-3	Summary of Major Process Characterization Measurements	5-7
7-1	Summary of Low Sulfur Coal Analyses	7-3
7-2	Test Results for the 75% SO_2 Removal Set Point, 2:1 Air-To-Cloth Ratio Tests for Low Sulfur Coal Conditions	7-5
7-3	Comparison of Three Approaches to Calculating Reagent Ratios for the 75% Removal, Low Sulfur Coal Conditions	7-8
7-4	Test Results for the 75% SO_2 Removal Set Point, 2.3:1 Air-to-Cloth Ratio Tests for Low Sulfur Coal Conditions	7-12
7-5	Test Results for the 90% SO_2 Removal Set Point, Nominal 2:1 Air-to-Cloth Ratio Tests for Low Sulfur Coal Conditions	7-17
7-6	Test Results for the 75% SO_2 Removal Set Point, 2:1 Air-to-Cloth Ratio for Low Sulfur Coal Conditions (Low Boiler Load)	7-26
7-7	Test Results for the 75% SO_2 Removal Set Point, 2.3:1 Air-to-Cloth Ratio for Low Sulfur Coal Conditions (Low Boiler Load)	7-27
7-8	Test Results for the 90% SO_2 Removal Set Point, 2:1 Air-to-Cloth Ratio for Low Sulfur Coal Conditions (Low Boiler Load)	7-28
7-9	Summary of High Sulfur Coal Analyses	7-29
7-10	Test Results for the High Sulfur Coal, 90% Removal Set Point, 2:1 Air-to-Cloth Ratio Tests	7-31
7-11	Test Results for the High Sulfur Coal 90% Removal Set-Point Tests With Calcium Chloride Addition	7-41
7-12	Summary of Sulfuric Acid Concentration Measurements During High Sulfur Coal Tests	7-48
7-13	Results of Particulate Mass Loading Measurements During Low Sulfur Coal Test Conditions	7-51

LIST OF TABLES (Continued)

Table		Page
7-14	Results of Particulate Mass Loading Measurements During High Sulfur Coal Test Conditions	7-55
7-15	Results of Several Spray Dryer Bottoms Drop Out Rate Measurements	7-59
7-16	Comparison of the Results of the EPA/ERPI Test Program With Previous Joy/Niro Results For Low Sulfur Coal Firing at Riverside	7-59
7-17	Comparison of the Results of the EPA/EPRI Test Program With Previous Joy/Niro Results For High Sulfur Coal Firing at Riverside	7-61
8-1	Process Raw Material Consumption Rate Summary	8-2
8-2	Average Atomizer Power Requirements	8-4
8-3	Average Pressure Drop and Fan Power Values	8-5
8-4	Summary of Current Measurements on Minor System Power Demands	8-7
9-1	Operating Conditions for Waste Product Samples Collected During the Riverside System Characterization Program	9-3
9-2	Summary of Tests and Test Procedures for Riverside Dry FGD System Waste Products	9-5
9-3	Summary of Elemental Analyses on Riverside Waste Solid Samples	9-7
9-4	Concentrations of Soluble Anionic Species in Waste Products From the Riverside Test Program	9-10
9-5	Moisture Content, Acid Insoluble Content, and Water Insoluable Content in Waste Solids From the Riverside Test Program	9-13
9-6	Unconfined Compressive Strength (UCS) for Riverside Spray Dryer Waste Products	9-24
9-7	Average Permeability Coefficients for Compacted and Cured Riverside Spray Dryer Waste Products	9-27
9-8	Ratios of Concentrations to EP Toxicity Limits in EP Extracts of Spray Dryer Waste Products From Test Facility at Riverside Station	9-31

LIST OF TABLES (Continued)

Table — Page

9-9 Comparison of EP Extracts and Neutral Extracts in Uncured Samples of Solid Waste Material From the Riverside Test Program.. 9-33

9-10 Effects of Curing on Neutral Extracts of Riverside Waste Solids... 9-35

9-11 Effect of Curing on EP Extracts of Riverside Waste Solids... 9-36

9-12 Comparison of EP Extracts and Neutral Extracts in Cured Samples of Riverside Solid Wastes........................... 9-38

9-13 Fluoride, Chloride, Sulfate, and Nitrate Concentrations in Neutral Extracts of the Riverside Solid Waste Samples....... 9-39

9-14 Other Water Quality Parameters in Neutral Extracts of Riverside Solid Waste Samples.................................. 9-43

A-1 Description of the Solid, Liquid, and Slurry Sample Locations On the Dry Scrubbing System at the Riverside Generating Station.. A-7

A-2 Description of Flue Gas Sampling Locations on the Dry Scrubbing System at the Riverside Generating Station............ A-8

A-3 Summary of the Solid, Slurry, and Liquid Sampling Schedule.. A-9

A-4 Summary of Flue Gas Sampling and Analysis Procedures........ A-16

A-5 Summary of Physical and Chemical Analysis Procedures........ A-30

A-6 Elemental Detection Limits.................................. A-38

C-1 Conversion of British Engineering (English) Units to SI Units... C-2

D-1 Daily CEMS Span and Zero Drift Measurements During Low Sulfur Coal Testing... D-3

D-2 Daily CEMS Span and Zero Drift Measurements During High Sulfur Coal Testing... D-6

D-3 Calcium Duplicate Analysis Results.......................... D-16

D-4 Sulfate Duplicate Analysis Results.......................... D-17

D-5 Summary of Performance Audit Results........................ D-19

LIST OF TABLES (Continued)

Table Page

D-6 SO_2 Monitor Audit Results.................................. D-21

D-7 O_2 Monitor Audit Results.................................. D-21

D-8 Audit Results for Dionex SO_2 (As SO_4) Analyses.............. D-23

D-9 Precision of Method 6 Data.................................. D-24

D-10 Calcium Audit Results.................................. D-26

D-11 Orsat Audit Results.................................. D-27

D-12 Dry Gas Meter Audit Results.................................. D-29

D-13 Analytical Balance Audit Data.................................. D-30

D-14 ASTM Temperature Rise Thermometer Audit.................................. D-31

E-1 Riverside Low Sulfur Coal Elemental Analysis of Spray Dryer Waste Product.................................. E-2

E-2 Riverside High Sulfur Coal Elemental Analysis of Spray Dryer Waste Product.................................. E-3

E-3 Riverside High Sulfur Elemental Analysis of Spray Dryer Waste Product.................................. E-4

E-4 Concentrations of Major and Minor Species in Riverside Spray Dryer Waste Products (All concentrations are in weight percent).................................. E-5

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SECTION 1
INTRODUCTION

This report presents the results from a program entitled "Field Evaluation of a Utility Dry Scrubbing System." The objective of the program has been to acquire performance data on an operating, utility-scale, spray dryer-based, dry FGD system. The system was evaluated primarily to determine SO_2 and particulate removal performance and lime reagent comsumption. Other areas evaluated have included flue gas sulfuric acid (SO_3) removal, solid waste characteristics, and major component power consumption. The system chosen for evaluation is the Joy/Niro Demonstration Unit located at the Northern States Power Company (NSP) Riverside Station in Minneapolis, Minnesota. The Riverside system was chosen for this program because it is the first lime-based system in operation using a full-size (46 ft* diameter) spray dryer module. Testing was conducted for the Environmental Protection Agency, Industrial Environmental Research Laboratory in Research Triangle Park, and for the Electric Power Research Institute under a cooperative funding arrangement.

1.1 BACKGROUND

This test program was desirable for several reasons. First, a significant number of spray dryer-based, dry FGD systems have been sold to the utility industry. At least 17 systems representing approximately 6,800 MW of electric generating capacity have been sold. No independent evaluation of the technology is available to aid utilities purchasing dry FGD systems, since virtually all of the performance data have come from pilot- or demonstration-scale units operated by system vendors. Several full-scale systems are coming on-line, but little performance data on these systems have been published. A second consideration is that most of the new systems and all of the future systems must meet the 1978 New Source Performance Standards for coal-fired utility boilers, which call for 70 to 90 percent SO_2 removal on a 30-day rolling average basis and particulate emissions of 0.03 $lb/10^6$ Btu heat input or less. Few data exist to confirm the ability of full-size spray dryer-based dry FGD systems to achieve these levels of performance, particularly for high sulfur coal requiring 90 percent SO_2 removal. Also, the spray dryer-based systems sold to date have been justified using economics based on vendor guarantees for lime consumption. However, no independent evaluation of lime consumption on an operating full-scale system has been conducted. The program described in this report was designed to collect the type of data that can help determine the suitability of this technology for utility application.

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*British engineering units rather than SI units are used in this report because of customary usage in the electric power industry. Appendix C provides appropriate conversion factors.

Finally, this program has included a full-scale evaluation of calcium chloride addition to promote increased lime sorbent utilization. This technology, which has shown promise at the bench- and pilot-scale but had never been demonstrated at the full-scale, may expand the applicability of spray dryer-based dry FGD systems to higher sulfur levels than currently considered practical.

1.2 PROJECT DESCRIPTION

As mentioned above, the test program was conducted at the Riverside Station of the Northern States Power Company, in Minneapolis, Minnesota. The flue gas from Units 6 and 7 at that station, which have a nominal total generating capacity of 100 MW, is combined and treated by a Joy/Niro spray dryer/fabric filter FGD system.

The spray dryer was installed in 1980 as a demonstration unit by the system vendors. Because the spray dryer was installed as a demonstration unit, the spray dryer/baghouse system does not have all of the redundancy of equipment that a commercial system would have. Also, since this was the first full-scale FGD spray dryer system designed and built by the vendors, the design does not include the latest evolutionary design changes. However, the system is very similar in design to the first several Joy/Niro commercial systems.

The Riverside system is an ideal size for a characterization program such as this because it has one full-size (46 ft) spray dryer vessel with a single 700 hp atomizer. Thus, the exact dryer and atomizer module used in larger multi-module commercial systems is available for characterization, but being a single module system the characterization efforts are greatly simplified. Another benefit of conducting this program on the Riverside system is that the Units 6 and 7 boilers have the capability of firing either low sulfur or high sulfur coal. Consequently, this program was able to evaluate spray dryer operation on flue gas from both low sulfur and high sulfur coal firing at a single location.

During the low sulfur coal (nominal 1.2 percent) test period, both 75 percent and 90 percent SO_2 removal levels were evaluated. Additionally, 75 percent SO_2 removal was evaluated at a higher than normal air-to-cloth ratio at the fabric filter. For the high sulfur coal (nominal 3.4 percent) test conditions, only 90 percent SO_2 removal was evaluated. Both normal lime reagent and lime reagent enhanced by calcium chloride addition were tested.

The primary data collection focused on SO_2 removal and lime utilization. Overall SO_2 removal data were further broken down into individual spray dryer and fabric filter contributions to system removal levels. Also measured were SO_3 removal across the system, particulate mass loadings, and solid waste material characteristics. In order to acquire all of this information at each set of test conditions, the flow rate and chemical composition of virtually every major process stream in the system were regularly measured. In addition to using these raw data to calculate the information listed above, they have been used to conduct material and heat balances which verify the accuracy of the data collected.

1.3 REPORT ORGANIZATION

This report is organized into nine sections. Additionally, a number of appendices are included. Section 1 is the introduction to the body of the report. Section 2 presents the main conclusions from the program, and Section 3 includes recommendations for potential future efforts. The testing approach and results of the program are discussed in detail in Sections 4 through 9, as described below.

The main body of the report is contained in Sections 4 through 9. Section 4 is a detailed description of the Riverside system which was evaluated in this program. Section 5 describes the test program which was designed to provide the information of interest about the system. Actual results of the program are included in Sections 6 through 9. The operation of the Riverside spray dryer-based dry FGD system during the test program is discussed in Section 6. Flue gas SO_2 removal, SO_3 removal, and particulate control results are presented in Section 7. Data from the low sulfur tests and high sulfur tests are presented and discussed separately. Section 8 is a summary of process requirements. While lime requirements to achieve the various levels of SO_2 removal for each coal type are presented in terms of reagent ratio values in Section 7, actual quicklime consumption rates in tons per hour are summarized in Section 8. Also summarized are makeup water rates and electric power consumption. Finally, Section 9 discusses the properties of solid waste samples from the system which were collected during this test program. The solid wastes are evaluated with respect to permeability coefficients, leachate chemical analyses, and unconfined compressive strength.

SECTION 2

SUMMARY AND CONCLUSIONS

The first part of this section summarizes the major results of this test program. Results summarized include system operation during the program as well as emission control performance, power consumption, and waste solids characteristics. The latter part of the section presents several conclusions relative to the state-of-the-art of spray dryer-based dry FGD for utility applications, based on the performance of the Riverside system.

2.1 SUMMARY

The summary of the results of this test program are divided into several subsections. Summaries are provided for system operation, SO_2 removal and lime reagent consumption, sulfuric acid removal, particulate removal, power consumption, and waste solids characteristics.

2.1.1 System Operation

In general, the Riverside system ran quite well. None of the problems anticipated for spray dryer systems such as rotary atomizer wheel pluggage, buildup of wet solids on dryer vessel walls, or wetting of fabric filter bag surfaces during upset conditions were observed. It should be noted that the majority of the test program involved boiler loads which resulted in flue gas residence times in the spray dryer vessel which were greater than the design value of 12 seconds. Long-term effects, such as spray dryer effects on fabric filter bag life or corrosion on fabric filter compartment walls, could not be evaluated within the 3-month duration of this project.

Some problem areas at Riverside appear to be potential sources of problems on other similar dry FGD systems. These include typical problems with mixing and pumping slurries with a high solids content, solids handling equipment which requires continual maintenance, sometimes inadequate atomizer protection during upset conditions, and ball mill slaker lime feed pluggage. These problems do not appear to limit this FGD technology. Instead, they appear to be solvable through consideration at the system design stage or with proper system operating procedures.

Other than these problem areas addressed above, the majority of the operating problems observed at Riverside appeared to be site-specific. Most were related to the system being a demonstration unit, and to the lack of utility operating experience as NSP had only recently assumed full responsibility for the operation of the system.

2.1.2 SO_2 Removal and Lime Reagent Consumption Performance

In the low sulfur coal tests, SO_2 removal levels of 75 to 90 percent appeared to be readily achievable for the short-term tests conducted. However, the system SO_2 removal did not always average the desired level of either 75 or 90 percent during steady-state conditions. This was most likely due to the removal set point on the process control computer not being set somewhat above the desired level to compensate for minor upsets. The actual average SO_2 removal levels of 74 to 89 percent were achieved with slightly substoichiometric amounts of lime. The fact that substochiometric amounts of lime were required indicates that the alkaline Sarpy Creek fly ash contributed to SO_2 removal.

In the high sulfur coal tests, SO_2 removal during steady-state operating conditions averaged approximately 2 percent below the set point value of 90 percent. The fact that the SO_2 removal set point was not raised to somewhat above the desired level to compensate for minor upsets was likely a contributor to this shortfall. Also, limitations on the flow of slaking and dilution water to the attrition slaker, imposed by the slaking water supply piping size, restricted the maximum lime slaking rate to just above the steady-state lime slaking rate for this test period. This restriction on lime slaking rate slowed the recovery of the SO_2 removal by the system after minor process upsets and was very likely a contributor to the shortfall of the average SO_2 removal below the set point value. It should be noted that the system was originally intended to operate under high sulfur coal conditions with both the ball mill and attrition slakers in service, hence the water piping to the attrition slaker was undersized when this slaker alone was supplying the entire lime requirement.

The average of 88 percent SO_2 removal during steady-state operating conditions was achieved at a lime reagent ratio of 1.3. Although 90 percent SO_2 removal was not achieved as an average for these short-term tests, partially due to the marginal lime slaking rate capability described above, short term SO_2 removal levels of 90 percent and higher were observed.

Calcium chloride addition at a rate which resulted in a one percent chloride level in the solids collected in the fabric filter was found to reduce reagent ratio requirements by about 25 percent for high sulfur coal in the 90 percent SO_2 removal set point tests. Preliminary economics based on estimated delivered costs for quicklime and bulk calcium chloride flake indicate that calcium chloride addition could be cost effective in reducing system lime consumption in high sulfur operation. The effects of chloride addition on corrosion in the system could not be evaluated. Because of the short-term nature of these tests, corrosion was not addressed in this program. However, no evidence of increased corrosion rates was observed. Effects of chloride addition on waste solids disposal characteristics are described below.

2.1.3 Removal of Flue Gas Sulfuric Acid Content

Measurements were made for the determination of the percent removal of flue gas sulfuric acid across the system. However, the results of measurements made during the low sulfur coal test period are difficult to interpret.

The presence of SO_3 in the flue gas at the spray dryer inlet could not be detected by the controlled condensation method. This finding was attributed to SO_3 absorption by the alkaline Sarpy Creek coal ash. However, it is not clear whether all SO_3 produced in the boilers was absorbed by the alkaline ash in the boiler or inlet flue gas duct work, or whether SO_3 was present in the flue gas at the spray dryer inlet sampling location and was absorbed by ash collected on the filter in the controlled condensation sampling train. Measurements at the fabric filter outlet sampling location, where virtually no particulate matter was present to potentially confound the determination, showed SO_3 levels which were below the detection limits of the measurement technique. The detection limit is approximately 0.1 ppm. Thus it is not clear whether no SO_3 was present in the flue gas at the spray dryer inlet at all, or whether SO_3 was in fact present and could not be successfully measured, and in turn was completely removed across the system.

Interpretation of results from the high sulfur coal test period is more straightforward. During the high sulfur coal tests, spray dryer inlet SO_3 concentration values measured ranged from 2 to 6 ppm. Concentrations measured at the fabric filter outlet were all below 1 ppm. Based on a limited number of spray dryer inlet and fabric filter outlet SO_3 concentration measurements conducted approximately simultaneously, SO_3 removal levels across the system of around 90 percent were indicated.

2.1.4 Particulate Removal

Mass loading measurements showed that particulate loadings at the spray dryer outlet were increased by a factor of 3 to 4 during low sulfur coal tests, and by a factor of 5 during high sulfur coal tests. Spray dryer outlet mass loadings ranged from 12 to 16 gr/dscf. Fabric filter outlet mass loadings were measured as high as 0.008 gr/dscf during a period when a bag-related problem was experienced in one compartment. Normal mass loadings ranged from 0.001 to 0.003 gr/dscf. Emission rates were as high as 0.022 $lb/10^6$ Btu while the bag-related problem was encountered, but normally ranged from 0.002 to 0.007 lb/10^6 Btu. Even this highest emission rate was below current NSPS-mandated levels for utility boilers.

It should be noted that fabric filter outlet mass loadings were measured using EPA Method 17. Previous measurements at this site conducted by NSP and Joy, employing EPA Method 5, indicated higher emission rates.[1]

2.1.5 Power Requirements

Power requirements were primarily determined for the two largest consumers in the system: the rotary atomizer and the induced draft (ID) fans. Atomizer power measurements were found to agree with a predictive correlation provided by Niro Atomizer to within 8 percent. The correlation uses the mass feed rate of atomizer feed slurry to predict atomizer power requirement. During the low sulfur coal, 90 percent SO_2 removal set point test period, which averaged 99 percent of design flue gas flow rate to the spray dryer, measured atomizer power requirements averaged 96 percent of the atomizer drive motor rating of 700 horsepower. Atomizer power requirements during the other test periods were well below the rated value.

Induced draft fan power requirements were calculated based on observed pressure drops across the spray dryer vessel, duct work, and fabric filter, and flue gas flow rates. The calculated power requirements were of approximately the same magnitude as the atomizer power requirement. Power requirements for electric motors in the lime slurry and atomizer feed preparation areas were also measured. The total power requirement for this area was only 20 percent of that required by the atomizer. Power requirements for the dry waste solids handling equipment were not measured.

2.1.6 Waste Solids Disposal Characteristics

A laboratory-scale characterization of solid waste samples collected during this program indicates that the cured samples from the low sulfur coal tests and the baseline high sulfur coal tests had unconfined compressive strength values that should allow landfilling the material. The samples from the high chloride test showed poorer values for unconfined compressive strength. These values were on the borderline for being adequate to allow landfilling. Also, the samples from the low sulfur and high sulfur baseline tests had permeability coefficients in the range of 10^{-5} to 10^{-7} cm/sec. These values are typical for FGD sludges. The permeability coefficient for the high chloride test was approximately 10^{-4} cm/sec, indicating that free moisture would more readily leach through a landfill of this material. These results indicate that although chloride addition was effective in reducing lime reagent consumption rates, it may have negative impacts on solid waste disposal characteristics. It is not certain from these results whether the apparent detrimental effect of chloride addition is a result of the high chloride levels alone or whether the fact that little excess lime is present in these wastes to promote cementation reactions also contributes.

All three samples tested were found to meet the requirements of the EP toxicity test for being classified non-hazardous.

2.2 CONCLUSIONS

Based on the results of this program, as summarized above, several conclusions about the state-of-the-art of spray dryer-based dry FGD technology are apparent. These conclusions are discussed below.

2.2.1 System Operation

Regarding system operation, no technology limiting problems were observed. The problems originally anticipated for spray dryer-based dry FGD systems, such as wetting of dryer vessel walls or wetting and "cementing" of fabric filter bags, were not observed to occur. The problems that were observed appear to be either site-specific, or potentially correctable in subsequent designs.

However, it is clear from observing the operation of this system that spray dryer-based dry FGD technology is not as simple as originally thought. The advent of solids recycle in particular has added to the mechanical complexity of the system as extensive solids handling equipment, additional mix tanks, slurry solids content measurement and control, pumping of high weight percent solids, etc., are involved. Compared with wet lime/limestone scrubbing, the overall process chemistry, though, is relatively straightforward. Most sorbent dissolution, chemical reactions, and solids precipitation occur while droplets are suspended in the dryer. In contrast, in wet scrubbing systems problems with scaling, which are related to the process chemistry, can occur in pumps, tanks, on absorber vessel internals, mist eliminators, or anywhere in the system where sorbent dissolution, SO_2 removal, or solids precipitation can take place.

The process control for a spray dryer-based dry FGD system requires measurement and control of approach to adiabatic saturation, feed slurry lime content, and feed slurry solids content, while wet FGD processes are often operated with not much more than pH and percent solids control. Spray dryer-based dry FGD systems employing rotary atomization also require the maintenance of large, high speed rotating devices. The rotary atomizer on this system was not observed to be trouble-prone; however, it required careful operation and maintenance.

This comparison of wet and dry scrubbing could be expanded to include an entire section or perhaps an entire report. However, the point of this discussion is that spray dryer-based dry FGD technology is not simple, and like wet scrubbing will require a knowledgeable and well-trained operating staff in order to operate successfully.

2.2.2 SO_2 Removal Performance and Lime Reagent Consumption

The results of this program confirm that up to 90 percent SO_2 removal can be achieved with a spray dryer-based dry FGD system for a coal sulfur content of up to 3.4 percent. However, because of the short-term nature of these tests, these data cannot be used to confirm the ability of such a system to achieve 90 percent SO_2 removal on a 30-day rolling average basis. Nor can the data be used to directly predict what SO_2 removal set point and corresponding lime reagent ratio values could conceivably be required to achieve such an average.

Average SO_2 removal levels of nearly 90 percent were achieved with a 3.4 percent sulfur coal; however, the test program did not establish the maximum levels which could be achieved. The economic limit for application of this technology will be affected by numerous site-specifics, such as flue gas temperatures, boiler excess air levels, and the cost of lime reagent. However, chloride addition, by reducing lime reagent ratio requirements during high sulfur operation, could expand the applicability of spray dryer/baghouse FGD systems to higher sulfur levels than are currently considered economically feasible. The effects of high chloride levels on system corrosion and on solid waste characteristics must be evaluated before commercial application of this technology.

Finally, these results confirm that for low sulfur coal operation with alkaline coal ashes, substoichiometric amounts of lime can achieve requisite (compliance) SO_2 removal set-point values. That is, fresh lime reagent utilization values of greater than 100 percent are possible, apparently due to the contribution of alkaline ash to SO_2 removal.

2.2.3 Particulate Removal

Particulate emission rate data from this program indicate that a fabric filter downstream of a spray dryer used for FGD service can consistently achieve emission levels below that mandated in the current New Source Performance Standards for utility boilers. Also, in spite of a particulate loading several times what fabric filters in regular flue gas service are subjected to, fabric filter flange-to-flange pressure drop downstream of a spray dryer remains acceptably low. The flange-to-flange pressure drop values observed during this program appear to be consistent with estimates that have previously been used to establish the economics of spray dryer/ baghouse dry FGD systems.

2.2.4 Waste Disposal Characteristics

Waste solids from this spray dryer-based dry FGD system appear to have acceptable landfill disposal properties, with acceptability high unconfined compressive strengths of 55 to 170 psi, and permeability coefficients of 10^{-4} to 10^{-6} cm/sec in cured samples that had optimum moisture levels added. However, an additional conclusion can be made about the quantity of wastes produced. If optimum compacted density, maximum values for unconfined compressive strength, and minumum values for permeability coefficient are desired, significant quantities of water may need to be added to the wastes. The results of the solid waste characterization study for this program indicate that optimum solid waste strength and permeability values were achieved at moisture levels in the three solid waste samples ranging from 24 to 32 percent in the wetted sample (32 to 48 g water added per 100 g of samples). In this instance, both the water consumption and the volume of wastes produced by the "dry" system would not be significantly different from those for a wet system where the FGD sludge is dewatered and subsequently blended with flyash. Of course if only minimum moisture to avoid dusting is added to the dry FGD wastes, the water requirements can be significantly reduced. Also, if ponding of wet FGD sludge without prior dewatering is compared, the water consumption and volume of wastes produced by the "dry" system is much smaller.

2.3 REFERENCES

1. Kaplan, Steven M., et al, "Dry Scrubbing at Northern States Power Company Riverside Generating Plant," presented at the EPA/EPRI Symposium on Flue Gas Desulfurization, Hollywood, Florida, May 17-20, 1982.

SECTION 3

RECOMMENDATIONS

Two major spray dryer/baghouse dry FGD evaluation parameters could not be characterized in this program. One evaluation parameter that could not be addressed was system availability. A key to the further acceptance of these systems in the electric utility industry is the availability demonstrated by commercial, multimodule systems now becoming operational. The availability of the Riverside system is not considered typical of a state-of-the-art commercial spray dryer based dry FGD system. Consequently, the availability of the system during this program is not reported. Availability of a commercial state-of-the-art system should be determined in a relatively low level of effort program aimed at documenting this parameter only. Potential sites for this evaluation could include the Basin Electric Cooperative Antelope Valley Station in Beulah, North Dakota, or the Sunflower Electric Cooperative Holcomb Station in Garden City, Kansas. Both of these systems are Joy/Niro spray dryer/baghouse systems. However, the SO_2 removal requirement for the Antelope Valley system is currently below that of the 1978 NSPS for low sulfur coal firing. Another potential site for evaluation is the General Electric system at the Shiras Station in Marquette, Michigan. This site, like the Riverside station, has only a single 36-ft. diameter dryer module and may not be representative of availability in multi-module systems. Other operating utility systems involve soda ash reagent, and/or once-through operation, and may not be typical of the majority of planned systems.

The second parameter which could not be evaluated at Riverside due to budget limitations on the duration of the program was the SO_2 removal set point and reagent ratio values which would be required to achieve 90 percent

SO_2 removal on a 30-day rolling average basis at a commercial utility installation. This is particularly a key issue on units where a high sulfur coal is burned. Unfortunately, no currently available sites are obvious locations to potentially conduct such a program. The only spray dryer-based systems currently in operation in high sulfur coal applications are industrial units. Data from such systems cannot be directly applied to utility installations, because smaller modules are used, and higher inlet flue gas temperatures are generally experienced. The high sulfur coal spray dryer demonstration unit being planned by TVA for retrofit to one unit at their Shawnee station may provide the first opportunity to establish these values.

One significant result from this program has been to demonstrate on a full-scale unit the effectiveness of calcium chloride addition in reducing lime reagent consumption on a high sulfur system. The potential benefits of chloride addition at varying rates for a wide range of coal sulfur levels can suitably be determined in an extensive pilot-scale test program. However, the potential problem of increased corrosion, particularly downstream of the spray dryer, could not be evaluated in this short-term test and may not be best evaluated at the pilot scale. Before calcium chloride addition is employed on a commercial full-scale high sulfur coal application, this issue should be addressed. Potential corrosion problems could be evaluated in a closely monitored long-term test of calcium chloride addition on a high sulfur industrial system. Such a program should be relatively inexpensive to conduct, because the cost of calcium chloride reagent should be offset by savings in lime consumption. Such a program would provide an opportunity to further study the impacts of high chloride levels on solid waste disposal characteristics.

Additionally, this program has characterized only a spray dryer/baghouse system. If spray dryer-based FGD technology is to see widespread application as a retrofit to existing high sulfur coal-fired boilers, particularly as a response to potential acid rain mitigation efforts, the operation of a spray dryer/electrostatic precipitator (ESP) system must be characterized. Two issues for these potential systems are the impacts of employing an ESP rather than a fabric filter on overall SO_2 removal efficiencies and the impacts of a spray dryer upstream on the emission rates from and the operation of an existing ESP. Pacific Power and Light Company has recently announced that spray dryers will be retrofitted for SO_2 control upstream of existing ESPs at their Wyodak station in northern Wyoming. When this retrofit comes on line in 1986, this will represent an excellent opportunity to characterize a full-scale retrofit spray dryer/ESP dry FGD system at a U.S. utility site. However, this will be a low sulfur system, and involves an existing large specific collection area (SCA) precipitator. Most high sulfur retrofit situations would involve precipitators with relatively low SCA values. Other potential sites for such a characterization might be the Basin Electric Laramie River Unit 3, (now in a pre-commercial operation phase), and the Grand River Dam Authority Pryor Station Unit 2 (scheduled for start-up in March 1985). Either of these ESP-equipped units could be available for such a characterization in the near future, but both are low sulfur coal systems with relatively large SCA precipitators.

Another approach to characterizing spray dryer/ESP system operation would be to conduct tests in a pilot-scale system. The best approach to conducting such a study would be to locate the pilot spray dryer and ESP adjacent to an existing high sulfur coal-fired utility boiler and use air heater exit flue gas as a flue gas source for the pilot unit. Comparison of baseline pilot ESP performance with performance downstream of the spray dryer could be used to predict spray dryer impacts on full-scale ESPs. Also, pilot plant data could be used to quantify ESP SO_2 removal levels and ESP impacts on overall system SO_2 removal capabilities.

Finally, several other issues remain unresolved after completion of this program. One question which will impact spray dryer/baghouse dry FGD economics is the long-term bag pressure drop performance and bag life downstream of a spray dryer. Also, the long-term effectiveness of employing mild, low carbon steel for materials of construction throughout the system has not been demonstrated. These questions may be resolved for low sulfur coal applications by monitoring the long-term performance of one or several of the commercial utility units now on line or soon to be on line. However, for high sulfur coal applications, the questions may not be resolvable in the near term. Results from pilot- or industrial-scale high sulfur coal units may provide some information, but differences in the way these units are operated relative to utility-scale units will confound these results. These issues may be best addressed in a high sulfur coal demonstration unit, such as that being planned by TVA for their Shawnee station.*

Also, the properties of the waste solids produced should be further characterized. The effects of chloride addition and/or use of waste water streams with high dissolved ion contents for solids moistening and compacting can be qualitatively addressed in laboratory studies of wastes from pilot- or utility-scale facilities. However, the disposal properties of spray dryer-based FGD wastes should ultimately be evaluated by the characterization of a landfill of wastes from a full-scale system.

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*See Joy/Niro comments in Appendix F.

SECTION 4
SYSTEM DESCRIPTION

4.1 TEST SITE

As described in the introduction, the spray dryer evaluation program was conducted at Northern States Power (NSP) Company's Riverside generating station which is located on the east bank of the Mississippi River in northeast Minneapolis, Minnesota. The spray dryer/fabric filter system treats the combined flue gas from Units 6 and 7 which currently have a total nominal generating capacity of 100 MW. When commissioned in 1949, Units 6 and 7 were designed to fire a high-sulfur bituminous coal, but in 1973 NSP began firing a coal blend consisting primarily of low-sulfur western (Sarpy Creek) coal to comply with SO_2 emission regulations. A small amount (10 to 15 percent) of high sulfur petroleum coke is added to the subbituminous coal to improve its firing properties. Units 6 and 7 can still, however, be fired with high-sulfur coal, and in fact they were for 5 weeks of the spray dryer evaluation program.

Units 6 and 7 are used for peaking in the NSP system and thus, during the cooler months of the year (October to June), are rarely operated. On weekdays during the summer, the units are operated at up to 95 MW during the day and at minimum load (about 50 MW) during the night. The units are normally banked over the weekend. This type of boiler operation results in repeated load swings which preclude long-term steady-state operation of the FGD system.

In 1980, a full-scale, Joy/Niro, spray dryer/fabric filter, FGD system was retrofitted to treat the combined flue gas from Units 6 and 7. The fabric filter was actually purchased by NSP because of the inability of existing ESP collectors to efficiently collect the ash from the western coal. The spray dryer system was installed by Joy/Niro under a cooperative agreement with the utility to serve as a full-scale demonstration of the capabilities of the dry FGD system.

4.2 OVERALL FLOW SCHEME

Figure 4-1 is an overall schematic of the pollution control system at NSP's Riverside station. As shown, flue gas from Units 6 and 7 enters a common duct and the combined gas stream is then redivided to flow to roof and central gas dispersers in the spray dryer. In the dryer vessel, the flue gas is mixed with an atomized slurry of lime ($Ca(OH)_2$) and recycled product (i.e., fly ash, $CaSO_4$, $CaSO_3$, $CaCO_3$, and unreacted $Ca(OH)_2$). This mixing results in droplet drying and simultaneous SO_2 removal. Flue gas and most of the particulates then exit the dryer and enter a 12-compartment fabric filter where 99.99 percent of the particulates are removed. Some particulates also drop out in the dryer vessel and are conveyed to a hopper for recycle to the process. Particulate collected in the fabric filter may either be recycled or conveyed to disposal. The particulate-free gas stream which exits the fabric filter is split again before it passes through the system induced draft (ID) fans and is then discharged through the original Unit 6 and 7 stacks.

Reagent slurry for the spray dryer system is prepared in several steps. Quicklime is slaked in either an attrition or ball mill slaker, processed in a spiral classifier for grit removal, and then fed to an agitator-equipped mixing tank. In the mixing tank lime reagent slurry, recycle solids from the spray dryer and fabric filter, and water are mixed to obtain a 35 weight percent solids slurry. This reagent slurry is pumped to a second agitator-equipped tank and then to a head tank which supplies the atomizer.

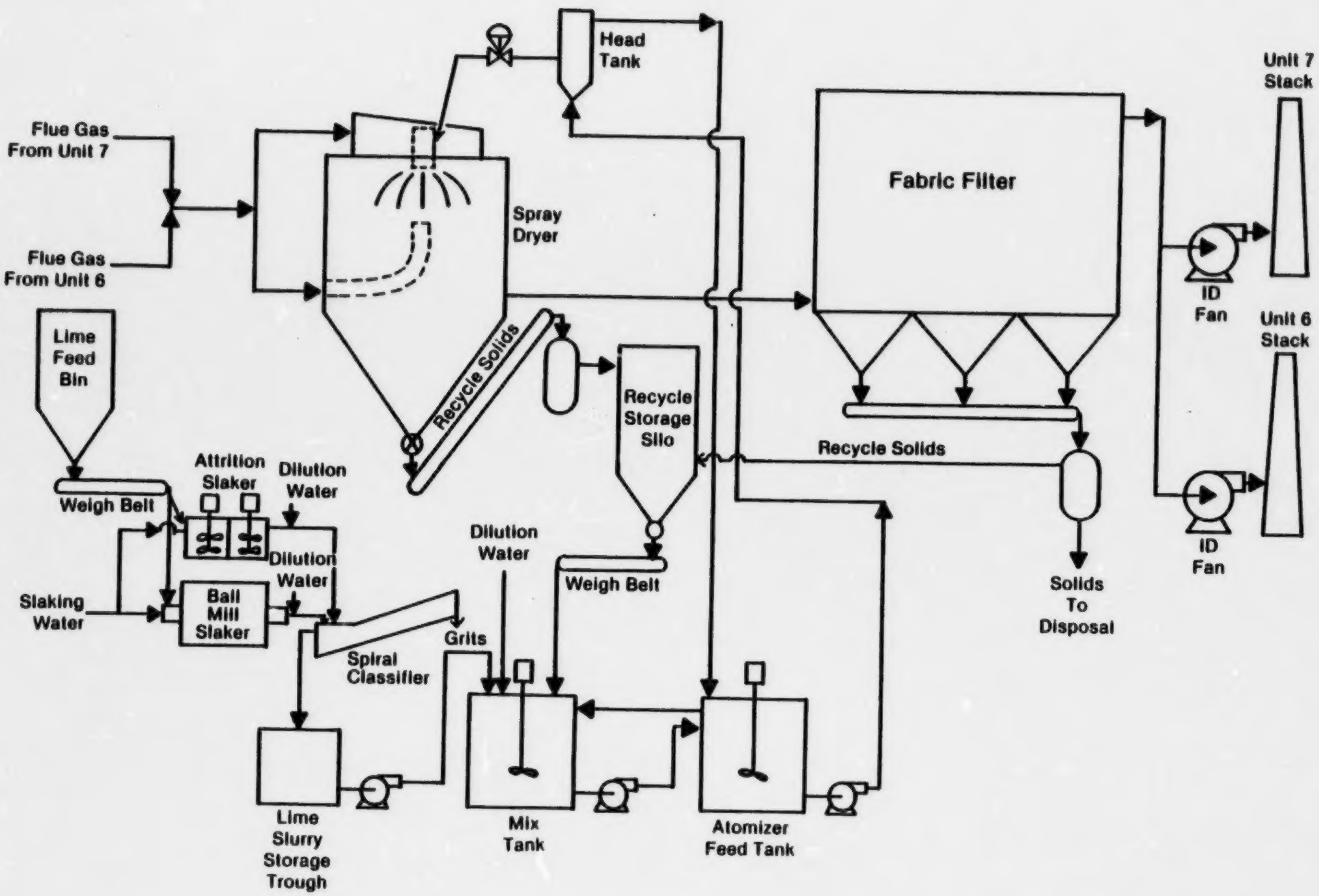
Flue Gas
From Unit 7
Flue Gas
From Unit 6
Spray
Dryer
Head
Tank
Fabric Filter
Unit 7
Stack
Unit 6
Stack
ID
Fan
ID
Fan
Recycle Solids
Recycle
Storage
Silo
Recycle Solids
Solids
To
Disposal
Lime
Feed
Bin
Weigh Belt
Attrition
Slaker
Dilution
Water
Dilution
Water
Slaking
Water
Ball
Mill
Slaker
Spiral
Classifier
Grits
Dilution
Water
Weigh Belt
Lime
Slurry
Storage
Trough
Mix
Tank
Atomizer
Feed Tank

Figure 4-1. Overall flow diagram for the Riverside dry FGD system.

4.3 PROCESS SUBSYSTEMS

The spray dryer/fabric filter system at NSP's Riverside generating station consists of six major subsystems:

- Spray Dryer/Atomizer,
- Fabric Filter,
- Reagent Preparation,
- Atomizer Feed Preparation,
- Solids Handling, and
- Process Control.

The following discussion presents details of each of these subsystems including typical modes of operation, capacities, residence times, sizes, etc.

4.3.1 Spray Dryer/Atomizer

The Niro spray dryer has a cylindrical top and a 60° conical bottom. The cylindrical portion of the dryer is 46 feet in diameter and 36 feet high. The dryer has a gas residence time of about 12 seconds at the design gas flow of 500,000 acfm. During this evaluation program, full-load residence times ranged from 12 to 14 seconds. Approximately 65 percent of the flue gas enters the dryer chamber through a roof gas disperser located above the atomizer wheel, while the other 35 percent of the gas enters through a central gas disperser located below the atomizer wheel (see Figure 4-1). Vanes in the gas dispersers swirl the gas streams to improve mixing between the flue gas and atomized slurry droplets.

The spray dryer is equipped with a side gas exit which results in some particulate fallout in the dryer chamber. Fallout is removed from the dryer through tipping valves and mechanically conveyed to a hopper which feeds a pneumatic conveying system. All of the particulate which is collected in the spray dryer chamber is recycled to the process. The atomizer is centrally located in the top of the dryer vessel and is gear-driven at 10,500 rpm by a 700 hp motor. The atomizer wheel is 350 mm (13.8 in.) in diameter and has twelve 6mm (1/4-in.) diameter circular nozzles. Slurry is fed to the atomizer from a constant level head tank. The feed rate is controlled by an air-actuated pinch valve.

4.3.2 Fabric Filter

Flue gas and entrained particulates exit the spray dryer through a side gas exit duct and enter a twelve-compartment fabric filter. These twelve compartments are split into two rows of six. Each row of compartments is emptied by a mechanical conveyor which removes particulates from the hoppers after compartment cleaning. During most of the evaluation program, the number of operating compartments was adjusted to maintain an air-to-cloth ratio of approximately 2:1. This normally resulted in seven to ten of the twelve compartments being on line. The typical duration between cleaning for each compartment in the fabric filter is 1 hour.

Joy Manufacturing was conducting tests at the Riverside fabric filter during this characterization program to determine the performance of various filter-bag materials in spray dryer service. Consequently, six of the compartments employed filter bags of various materials while the remaining six had Menardi 601-T type (9.3 oz/yd^2 teflon-coated fiberglass) bags. Each compartment contains 250 bags which are 12 in. in diameter and 35 ft. long. Also, several compartment doors were treated with experimental coatings to evaluate their corrosion resistance in spray dryer associated service.

4.3.3 Reagent Preparation

The alkaline reagent employed in the Riverside spray dryer system is slaked lime. A schematic of the reagent preparation system is shown in Figure 4-2. It consists of facilities for off-loading quicklime from trucks, a quicklime storage silo, weigh belts to meter quicklime to the slakers, ball mill and attrition slakers, and a spiral classifier for grit removal. The slakers are sized to provide some excess capacity above the spray dryer's steady-state demand. However, there is no provision for any significant storage of slaked lime. Output of the slakers is fed from a small head tank (5-min. residence time) directly into the atomizer feed preparation system. This means that in the event of problems in the slaker system, the concentration of lime reagent in the atomizer feed slurry begins to decline immediately and within a short time (less than 30 min.) spray dryer SO_2 removal efficiency can be adversely affected.

Feed rates of quicklime and water to the slakers are computer-controlled to produce a lime slurry with a relatively constant weight fraction solids. The lime slurry production rate is controlled based on system demand. During the evaluation program, the system demand was the rate required to maintain a specified SO_2 removal efficiency in the spray dryer fabric filter system.

In normal operation, Riverside operating personnel prefer to operate the attrition slaker, which consists of two agitator-equipped slaking compartments in series. The agitator in each tank is equipped with opposite-pitched impellers on a common shaft. Design throughput for this unit is about 3 tons/hr of quicklime. This is about three times the required slaking rate for Riverside's typical operation for 75 percent SO_2 removal when firing the Sarpy Creek/coke blend fuel. It is just over the capacity required to achieve 90 percent SO_2 removal when firing a 3.4 percent sulfur Illinois coal as was done during the evaluation program.

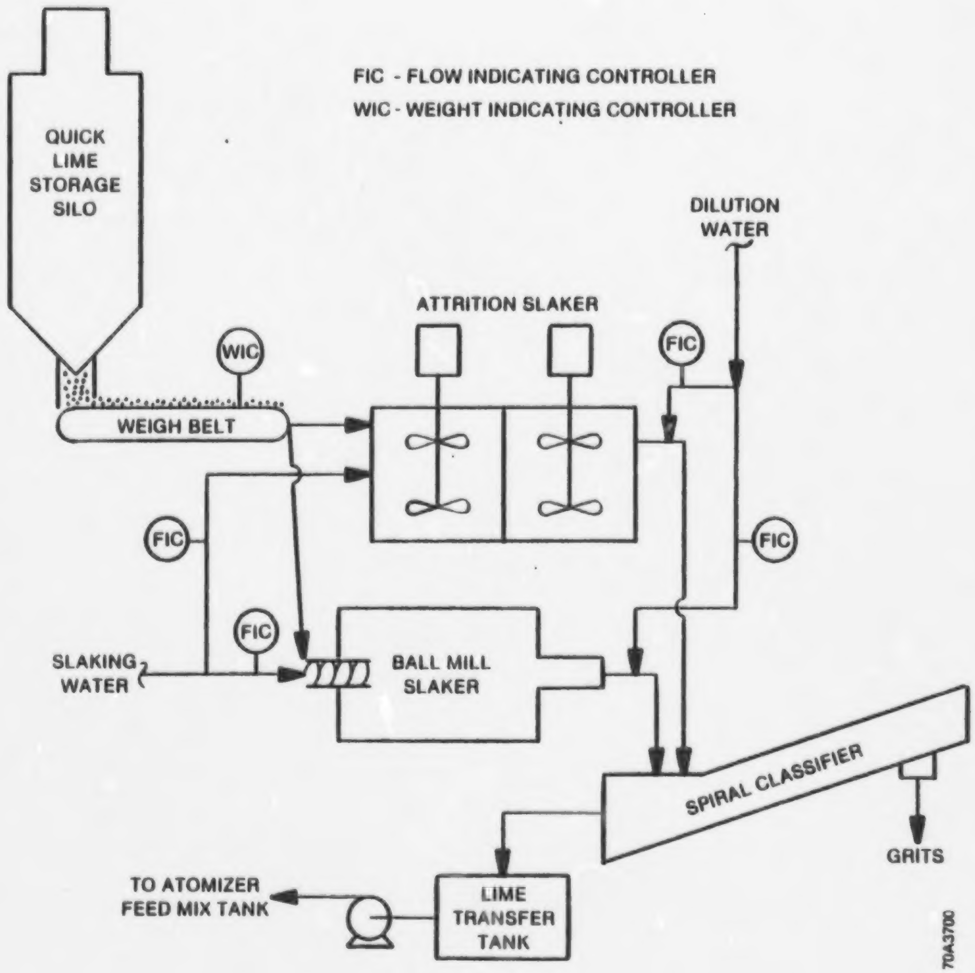
FIC - FLOW INDICATING CONTROLLER
WIC - WEIGHT INDICATING CONTROLLER
QUICK LIME STORAGE SILO
WIC
WEIGH BELT
ATTRITION SLAKER
FIC
DILUTION WATER
FIC
FIC
FIC
SLAKING WATER
BALL MILL SLAKER
SPIRAL CLASSIFIER
GRITS
LIME TRANSFER TANK
TO ATOMIZER FEED MIX TANK
70A3700

Figure 4-2. Schematic of the reagent preparation system.

The ball mill was included in the system to allow Joy/Niro to evaluate its performance as a slaker. However, it is not normally operated by NSP. Several attempts were made to test this slaker during the evaluation program, but the lime feed system plugged repeatedly. Because the lime preparation system has no storage capacity, slaker problems immediately interrupted the flow of lime slurry to the atomizer feed system. Consequently, attempts to employ the ball mill slaker were abandoned. This problem is discussed in more detail later in this report.

4.3.4 Atomizer Feed Preparation

The atomizer feed preparation system is used to mix and feed reagent slurry to the atomizer. It consists of two 8 ft x 11 ft diameter agitator-equipped tanks in series, two slurry transfer pumps (one operating and one spare), two 250 gpm rubber-lined slurry feed pumps (one spare and one operating), a weigh belt for metering recycle solids into the mixing tank, and process controls to regulate water and lime slurry addition rates and tank levels. This system is illustrated in Figure 4-3. As shown, lime slurry from the reagent preparation system, recycle solids, and water are mixed in the first of the two tanks. This mixture is pumped to the second tank and is then pumped to the atomizer head tank. The atomizer head tank provides a constant pressure slurry supply to the atomizer feed control valve which regulates flow of slurry to the atomizer wheel. Excess slurry fed to the head tank overflows back to the second atomizer feed tank. This tank in turn has a gravity overflow back to the mix tank. These overflows provide some backmixing between the two larger tanks and the small head tank.

The addition rates for lime reagent slurry, recycle material, and water to the mix tank are computer controlled. The total solids in the final mixture are controlled to maintain a level of about 35 weight percent. This level is considered necessary for production of dry solids in the dryer. The fraction of the total solids which is actually lime reagent can be controlled several ways. In typical operation prior to the evaluation program, NSP operating personnel maintained lime solids at a constant

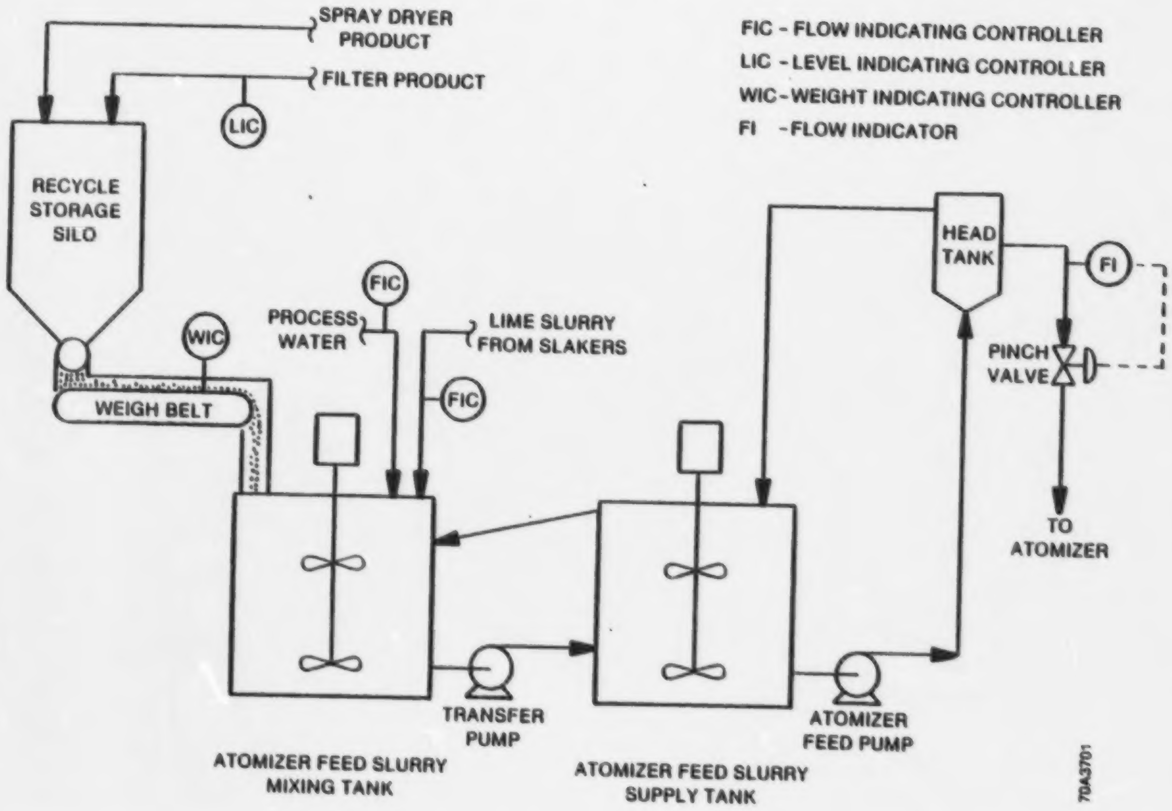
SPRAY DRYER PRODUCT
FILTER PRODUCT
LIC
RECYCLE STORAGE SILO
WIC
WEIGH BELT
FIC
PROCESS WATER
LIME SLURRY FROM SLAKERS
FIC
TRANSFER PUMP
ATOMIZER FEED SLURRY MIXING TANK
ATOMIZER FEED SLURRY SUPPLY TANK
ATOMIZER FEED PUMP
HEAD TANK
FI
PINCH VALVE
TO ATOMIZER
FIC - FLOW INDICATING CONTROLLER
LIC - LEVEL INDICATING CONTROLLER
WIC - WEIGHT INDICATING CONTROLLER
FI - FLOW INDICATOR
7DA3701

Figure 4-3. Schematic of the atomizer feed preparation system.

fraction of the feed slurry. During the evaluation program, this control scheme was changed to implement system SO_2 removal control. The lime slurry fraction of the feed was automatically adjusted by the control computer software to maintain a constant SO_2 removal efficiency across the spray dryer/fabric filter system.

Residence times in the atomizer feed and mix tanks vary depending on load, inlet flue gas temperature, and approach temperature. During the evaluation program, these times ranged from a total of 70 minutes to 90 minutes. This presented some problems in attempts to control SO_2 removal to a specified level. The control system adjusted the lime addition rate to the mix tank to account for deviations in SO_2 removal from the set point. However, the system's response to major changes in removal was quite slow due to the relatively long residence time in the mixing and supply tanks.

It should be noted that although the mixing and atomizer feed tanks have relatively long residence times, the tank volumes do not provide feed surge capacity. This is because it is necessary to operate the tanks at a level well above the agitator blades (at least a 6.5 ft slurry level). If tank levels drop too close to the level of the agitator blades, slurry is thrown to the tank walls where it can dry and form large deposits. These deposits break off and eventually plug screens in the system which are included to prevent large particles from entering the atomizer wheel. Such pluggage generally necessitates shutdown of the entire FGD system to permit cleaning.

4.3.5 Solids Handling

Solids handling in the Riverside spray dryer system employs both mechanical and pneumatic conveyors. The system includes drag chain and belt conveyors, surge bins, motor-driven tipping valves, and dense medium pneumatic conveyors which use "blow pots" to move particulates. The overall solids handling system at Riverside is shown as part of Figure 4-1. Solids are discharged from both the spray dryer and fabric filter through motor-driven tipping valves. Solids from the spray dryer are conveyed by a drag chain conveyor to a surge bin which feeds a blow pot. Solids from the 12 fabric filter hoppers are discharged onto two identical chain conveyors (one for each row of six compartments in the fabric filter). These conveyors then discharge into surge bins which feed blow pots.

The blow pots provide the transition from mechanical to pneumatic conveying of particulates. They operate through the following cycle:

- filling from the surge bin,
- isolation from the surge bin,
- pressurization,
- pneumatic conveying, and
- depressurization.

Discharge from the blow pots can be pneumatically conveyed to two destinations. All spray dryer solids are conveyed to the recycle silo. Fabric filter solids may either be recycled or conveyed to a disposal silo. Filter solids are recycled "on demand." A low-level indicator in the recycle silo causes fabric filter solids to be conveyed to the recycle silo until it is full. The remainder of the time, filter solids are conveyed to a disposal silo. Material from the disposal silo is then removed in trucks for final disposal as landfill.

4.3.6 Process Control

The Riverside spray dryer system employs a Honeywell process computer to control system operation and to provide safety interlocks for key items of process equipment, including the atomizer. Inputs to the computer system primarily include measurements of key process parameters. Both feed-back and feed-forward control systems are used to maintain system operation at desired levels. Table 4-1 is a list of the major process inputs to the system, but represents only a small fraction of the total computer inputs.

TABLE 4-1. KEY PROCESS CONTROL MEASUREMENTS

Process Area	Key Measurements	Measurement Technique
Spray Dryer/ Fabric Filter	Gas Flow	Roof Gas Disperser ΔP
	Inlet Temperature	Resistance Temperature Device
	Outlet Temperature	Resistance Temperature Device
	Wet Bulb	Wetted Wick Thermocouples
	Inlet SO_2	DuPont 460
	Outlet SO_2	Lear-Siegler
	Filter ΔP	Pressure Transducer
	Atomizer Feed Rate	Magnetic Flow Meter
Reagent Preparation	Lime Feed Rate	Weigh Belt
	Water Feed Rate	Orifice - ΔP Transducer
Slurry Preparation	Lime Slurry Feed Rate	Magnetic Flow Meter
	Recycle Solids Rate	Weigh Belt
	Slurry Density	Density Meter
	Water Rate	Orifice - ΔP Transducer
	Tank Levels	Level Transducers
Atomizer	KW, KVA	Wattmeter, Ammeter
	Oil Temperature	Resistance Temperature Device
	Oil Pressure	Pressure Transducer
	Valve Position	Pressure Transducer

A brief discussion of major control loops used during the evaluation program is presented below.

Approach Temperature Control--

During most of the evaluation program, the spray dryer/fabric filter system was operated at a 20°F approach to saturation based on the fabric filter outlet wet bulb temperature. This corresponds to about an 18°F approach based on the spray dryer inlet wet bulb, because of heat losses in the dryer and fabric filter. The approach to saturation was automatically controlled by the process computer using a combination feed-forward feedback loop. The major control inputs were spray dryer outlet temperature and fabric filter outlet wet bulb temperature. Based on the difference between these values, the computer adjusted the atomizer feed slurry rate to maintain a constant approach to adiabatic saturation. Inlet flue gas flow and temperatures provided feed forward signals to the controller to prevent sudden load swings from causing process upsets. A sudden drop in flow, for example, would be sensed by the controller and the slurry feed rate would be reduced accordingly, rather than waiting for the outlet temperature to drop before reducing slurry flow. Several other safety interlocks are part of the approach temperature control system. Three wet bulb monitors provide signals to the computer. The average of these three values is used to determine the wet bulb supplied to the controller. If one of the wet bulb measurements is more than 4°F from the average, it is considered to be erroneous and is not included in the average calculation. If all three of the wet bulb measurements are more than 4°F apart, the computer simply controls the outlet temperature to a preset, safe level. Another interlock provided to prevent loss of control is activated if the approach temperature drops to less than 15°F. In this event, the system would automatically revert to a preset outlet temperature.

SO_2 Removal Efficiency Control--

In addition to controlling approach temperature, the process computer automatically controlled SO_2 removal efficiency in the spray dryer/fabric filter system. SO_2 removal efficiency control is a capability of typical Joy/Niro dry FGD systems, but had not previously been a capability of the Riverside demonstration system. This capability was specifically installed on the Riverside system process control computer for the purposes of this test program. This control system employed inlet and outlet SO_2 monitors to determine removal efficiency. The controller then adjusted the composition of the atomizer feed stream to obtain the desired SO_2 removal. The controller logic includes calculation of the current lime-to-SO_2 reagent ratio and an estimation of the change in reagent ratio required to achieve a desired level of SO_2 removal. As mentioned earlier, this control loop was quite slow. It involves actually adjusting the slaked lime production rate and requires changing the composition of the slurry in the mix and atomizer feed tanks. Because of the slurry residence times in these tanks, such changes often take several hours to be fully effected.

It should be noted that the approach temperature and SO_2 removal control loops could not function independently. The approach temperature loop adjusted the slurry feed rate to the atomizer to maintain a constant approach to adiabatic saturation. However, such an adjustment would also change the reagent ratio and consequently the SO_2 removal efficiency in the system. This would then require the SO_2 removal controller to respond accordingly.

Reagent Preparation Control--

The throughput of the reagent preparation system was controlled by the SO_2 removal control system. Lime and water feed rates were set to obtain a specific weight fraction solids in the slurry. The relative flows were maintained at a constant level while the actual flows were adjusted by the SO_2 removal control loop to respond to changes in demand for lime slurry.

Atomizer Feed Preparation Control--

This system was also controlled by the SO_2 removal controller. Relative addition rates of lime slurry, water, and recycle solids were adjusted to: (1) maintain 35 percent solids in the feed slurry and (2) obtain the desired SO_2 removal efficiency. Actual flows were varied to maintain the mix tank and atomizer feed supply tank at a constant level above the agitator blades.

SECTION 5

TEST PROGRAM DESCRIPTION

This section describes in further detail the test program that was conducted at the Riverside station. Included in subsection 5.1 is a description of the test plan, both as originally planned and as actually conducted. As discussed, not all conditions originally planned could be successfully tested. Subsection 5.2 discusses some of the modifications made on the system to facilitate this test program. These modifications primarily included adding a more complete continuous emissions monitoring system and adding percent SO_2 removal software to the process control computer. Finally, subsection 5.3 discusses some of the limitations of the Riverside system as a host site for this type of program.

5.1 TEST PLAN

The test plan originally designed for this program is summarized in Table 5-1. The test plan called for four different sets of operating conditions with the low sulfur fuel and three conditions with high sulfur fuel.

The low sulfur fuel is the normal fuel burned in the Riverside Units 6 and 7 boilers. It is a mixture of 88 percent Sarpy Creek subbituminous coal and 12 percent high sulfur coke. The high sulfur (nominal 3.4 percent) coal was purchased specifically for this program and was a Peabody Coal Company Illinois No. 6 coal.

The low sulfur test conditions called for overall SO_2 removal levels of 75 to 85 percent. These removal levels are typical of the removal levels of most spray dryer-based FGD systems burning western low sulfur subbituminous coals. The majority of the tests were to be conducted with the lime

TABLE 5-1. ORIGINAL TEST PLAN FOR THE RIVERSIDE SPRAY DRYER/BAGHOUSE CHARACTERIZATION

Boiler Fuel Type	Overall SO_2 Removal (%)	Slaker Type	Fabric Filter Air-to-Cloth Ratio (gross)	Baghouse Compartment Cleaning Frequency	Approach to Adiabatic Saturation (°F)[a]
Low Sulfur Coal	75	Ball Mill	2:1	Once per hour	18
Low Sulfur Coal	75	Ball Mill	2.7:1	Once per hour	18
Low Sulfur Coal	85	Ball Mill	2:1	Once per hour	18
Low Sulfur Coal	85	Attrition	2:1	Once per hour	18
High Sulfur Coal	90	Ball Mill	2:1	Once per hour	18
High Sulfur Coal	90	Ball Mill	2.7:1	Once per hour	18

[a] Based on wet bulb temperature at the spray dryer inlet. Actual set point for system approach temperature control was 20 °F, as continuous wet bulb temperature measurement is made at the fabric filter outlet, and the value measured is approximately 2 °F lower than that at the spray dryer inlet.

prepared in the ball mill slaker, because most systems previously sold by the Joy/Niro process vendors will reportedly employ ball mill slakers. One test with the attrition slaker was scheduled to evaluate any potential lime slaker impacts on lime consumption. Additionally, one test period was scheduled to be conducted at a fabric filter air-to-cloth ratio of 2.7:1. This test was to evaluate fabric filter air-to-cloth ratio effects on system pressure drop and on fabric filter SO_2 removal contributions.

The high sulfur coal test period originally included three sets of conditions. All tests were to be conducted at 90 percent overall SO_2 removal because current New Source Performance Standards for utility boilers would require that level of removal for this coal. Two tests were to be conducted with the ball mill slaker and one with the attrition slaker. One of the two ball mill-slaked lime test conditions involved operating the fabric filter at the higher 2.7:1 air-to-cloth ratio rather than at the normal 2:1 air-to-cloth ratio.

Due to problems that developed, this original test plan had to be modified. First, Northern States Power Company personnel at the Riverside station prefer to operate the attrition slaker rather than the ball mill slaker. The slaking area is rather confined and the ball mill slaker is relatively noisy to operate. Consequently, the test plan was modified to switch the ball mill slaker for the attrition slaker, and vice versa, in the test plan in Table 5-1. Thus, three of four tests at low sulfur conditions were to be conducted with the attrition slaker and just one with the ball mill slaker. Likewise for the high sulfur test period, two tests were to be conducted with the attrition slaker and only one test with the ball mill slaker.

However, in several attempts during both the low sulfur and high sulfur coal test periods, the ball mill slaker could not be made to operate successfully. The ball mill slaker problems are discussed in Section 6.2, Discussion of System Operation.

Another change to the original test plan required that the air-to-cloth ratio value for the high air-to-cloth ratio tests be lowered. The air-to-cloth ratio is increased at a constant boiler load by taking individual compartments off-line. After taking compartments off-line to raise the gross air-to-cloth ratio to near 2.7:1, only six of the twelve compartments remained on-line. The combined effects of taking an operating compartment off-line for cleaning and reverse gas flow during cleaning momentarily sends the effective air-to-cloth ratio to between 3.5:1 and 4:1. In a unit with more compartments on-line, the effects of cleaning one compartment in increasing the effective air-to-cloth ratio are much smaller. Additionally, in the event of a temporary loss of slurry flow to the atomizer while a compartment is cleaning, the increased flue gas volume due to the much higher spray dryer outlet temperature would result in a further increase in the effective air-to-cloth ratio to well over 4:1. When operated at such a high effective air-to-cloth ratio, the pressure drop across the fabric filter is increased to several times its normal value. Such a combination of events did occur on the first day of the low sulfur high air-to-cloth ratio tests, and the resulting momentary high pressure drop caused the control system to bypass the fabric filter. In order to provide a margin of safety, one more compartment was put on-line. This lowered the gross air-to-cloth ratio to 2.2:1 to 2.3:1, which is only 10 to 15 percent higher than baseline conditions. Because this air-to-cloth ratio represented such a limited increase above the normal air-to-cloth ratio, a higher air-to-cloth test was not conducted at the high sulfur coal test conditions.

Since the ball mill-slaked lime test conditions could not be run, and the higher air-to-cloth ratio test was eliminated from the high sulfur coal test schedule, time was available during the high sulfur test period to test an alternate set of conditions.

One of the system vendors, Niro Atomizer, recommended that this time period be used to conduct a full-scale evaluation of the effectiveness of calcium chloride addition to promote increased lime reagent utilization. Chloride addition had been reported previously to enhance lime utilization in spray dryer/baghouse FGD systems (1,2), but these previous studies had concerned only bench- and pilot-scale evaluations. The enhancement effect is thought to occur because of the deliquescent properties of calcium chloride. This effect is further described in Section 7.1, SO_2 Removal Performance.

The revised test schedule for this program is summarized in Table 5-2. Note that in addition to the test plan modifications described above, the SO_2 removal level for the low sulfur, increased SO_2 removal tests was raised from 85 to 90 percent. This change was made because it was felt that the difference in reagent ratio required to achieve 85 percent rather than 75 percent overall SO_2 removal would be difficult to evaluate at full scale. Raising the upper removal level effectively increased the difference between the reagent ratio requirements for the two conditions.

Table 5-3 summarizes some of the parameters measured during the test program. Also listed are the measurement techniques for each parameter. For all parameters continuously measured, values were recorded by either the Honeywell process control computer, or in the case of the continuous emissions monitoring system, by a Radian DART II data acquisition system.

The Riverside system was reasonably well instrumented for this program, due in part to its status as a demonstration system. Where posible, existing measurement devices were used. However, either manual alternate measurements or cross comparision of independent measurement techniques were used to verify temperatures, flow rates, and stream compositions. The data quality control techniques used in this program are discussed where appropriate in Section 7, Emission Control Performance, Section 8, Process Requirements, and Appendix D, Data Quality.

5.2 SYSTEM MODIFICATIONS

Primarily two modifications to the existing system were required before this test program began. One was the addition of a more comprehensive

TABLE 5-2. REVISED TEST SCHEDULE FOR THE RIVERSIDE SPRAY DRYER/ BAGHOUSE CHARACTERIZATION

Boiler Fuel Type	Overall SO_2 Removal (%)	Slaker Type	Fabric Filter Air-to-Cloth Ratio (gross)	Baghouse Compartment Cleaning Frequency	Approach to Adiabatic Saturation (°F)[a]
Low Sulfur Coal	75	Attrition	2:1	Once per hour	18
Low Sulfur Coal	75	Attrition	2.3:1	Once per hour	18
Low Sulfur Coal	90	Attrition	2:1	Once per hour	18
High Sulfur Coal	90	Attrition	2:1	Once per hour	18
High Sulfur Coal[b]	90	Attrition	2:1	Once per hour	18

[a] Based on wet bulb temperature at the spray dryer inlet. Actual set point for system approach temperature control was 20°F, as continuous wet bulb temperature measurement is made at the fabric filter outlet, and the value measured is approximately 2°F lower than that at the spray dryer inlet.

[b] Calcium chloride added to atomizer feed slurry to achieve a chloride level of one percent in the fabric filter solids.

TABLE 5-3. SUMMARY OF MAJOR PROCESS CHARACTERIZATION MEASUREMENTS

Parameter	Measurement Technique
Flue gas SO_2 and O_2 concentrations	Continuous monitors[a], EPA Method 6
Flue gas SO_3 concentrations	Manual controlled condensation measurements
Flue gas adiabatic saturation temperature	Continuous[a] and manual wetted-wick thermometers
Flue gas flow rate	Correlated to spray dryer roof gas disperser pressure drop (ΔP transducer)[a]
Flue gas temperatures	Resistance temperature devices[a]
Flue gas particulate mass loadings	EPA Methods 5 and 17
Quicklime feed rate to system	Weigh belt[a]
Lime slurry makeup rate to mix tank	Magnetic flow meter[a]
Lime slurry solids content	Manual gravimetric determination
Dilution water makeup rate to mix tank	Orifice meter[a]
Recycle solids rate to mix tank	Weigh belt[a]
Atomizer feed slurry flow rate	Magnetic flow meter[a]
Atomizer feed slurry percent solids	Density meter[a], manual determination by gravimetric analysis of grab samples
Fabric filter pressure drop	ΔP transducer[a]
Fabric filter air-to-cloth ratio	Calculated from flue gas flow rate, number of compartments on line
SO_2 removal	Calculated from continuous monitor data
Reagent ratio	Calculated from inlet SO_2 concentration measured by continuous monitors, inlet flue gas flow rate, lime consumption rate measurements
Waste product characteristics	Off-site analysis of 55-gallon drum sample collected during steady-state operation at each set of operating conditions
Power requirement	Manual measurements with voltmeter, clamp-on ammeter at individual motor control centers

[a] Continuously measured

continuous emissions monitoring system (CEMS). The second involved the addition of percent SO_2 removal control software to the Honeywell process control computer system. Each of these modifications is described below.

5.2.1 Continuous Emissions Monitoring System (CEMS)

At the beginning of the program, the only emissions monitor in service was a Lear-Siegler in-situ SO_2 monitor at the outlet of the fabric filter. The monitor was installed in a rather short run of duct at the outlet of the fabric filter, upstream of the point where the duct work splits to go to two separate I.D. fans and two separate stacks. For the purposes of this program, it was required that SO_2 removal across the system be monitored on a continuous basis, according to the provisions of the current New Source Performance Standards for utility boilers. This required that the spray dryer inlet SO_2 concentration be measured, as well as the fabric filter outlet SO_2 concentration which was already monitored. Also, a diluent gas such as CO_2 or O_2 needed to be monitored at each location, in order to correct for air inleakage.

Because this was a system characterization program rather than just an attempt to acquire compliance type data, it was also desirable to measure SO_2 and diluent gas concentration data at the spray dryer outlet. These concentration data allow measurement of the individual contributions of the spray dryer and fabric filter to overall system SO_2 removal.

In order to satisfy these requirements, a DuPont 460 two-point extractive SO_2 monitor was installed on site. The two points monitored were the spray dryer inlet and the spray dryer outlet ducts. Standard DuPont in-stack probes were placed at the centroid of each duct, and heat-traced sample lines were used to connect the sample points to the monitor. A Thermox Model WDG O_2 monitor was interfaced with the DuPont SO_2 monitor so that it measured the O_2 content of the gas sampled by the SO_2 monitor. The sample pickup for the Thermox O_2 monitor was extended across the duct to within one foot of the in-stack sample cell for the Lear-Siegler monitor.

The electrical analog output signals from the DuPont 460 monitor, the two Thermox WDG monitors, and the Lear-Siegler monitor were connected to a Radian DART II data acquisition system. The DART II converted all analog signals to concentration values, then recorded all concentration data as 5-minute averages throughout each test day. The 5-minute average SO_2 and oxygen concentration data from each of the three sampling locations were printed out every hour on a Teletype Model 43 local keyboard printer and stored on replaceable floppy discs.

Figure 5-1 is a schematic of the Riverside spray dryer/baghouse duct work, and depicts the three sampling locations. Figure 5-2 is a schematic of the continuous emission monitoring system described above, showing the interconnection between the four monitors and the data acquisition system.

It should be noted for discussions later in this section that the analog output from the DuPont 460 for the spray dryer inlet SO_2 concentration was connected to the Honeywell process control computer. The concentration data, combined with the outlet SO_2 concentration data from the Lear-Siegler monitor, allowed the process control computer to calculate SO_2 removal efficiencies across the system.

The CEMS as described above was certified, using the procedures specified in the Federal Register. The DuPont 460/Thermox WDG combination at the spray dryer inlet location passed the relative accuracy tests in the minimum nine measurements. The relative accuracy for the DuPont 460/Thermox WDG combination at the spray dryer inlet location was measured at value of 4.6 percent. The Lear-Siegler monitor required a service call from a field service representative for a minor adjustment, but afterward the Lear-Siegler/Thermox WDG combination at the fabric filter outlet also passed the relative accuracy tests at a value of 7.1 percent. Little emphasis was placed on 7-day span and zero drift check results, as it was known that the span and zero values for each monitor would be adjusted daily as needed to ensure optimum performance.

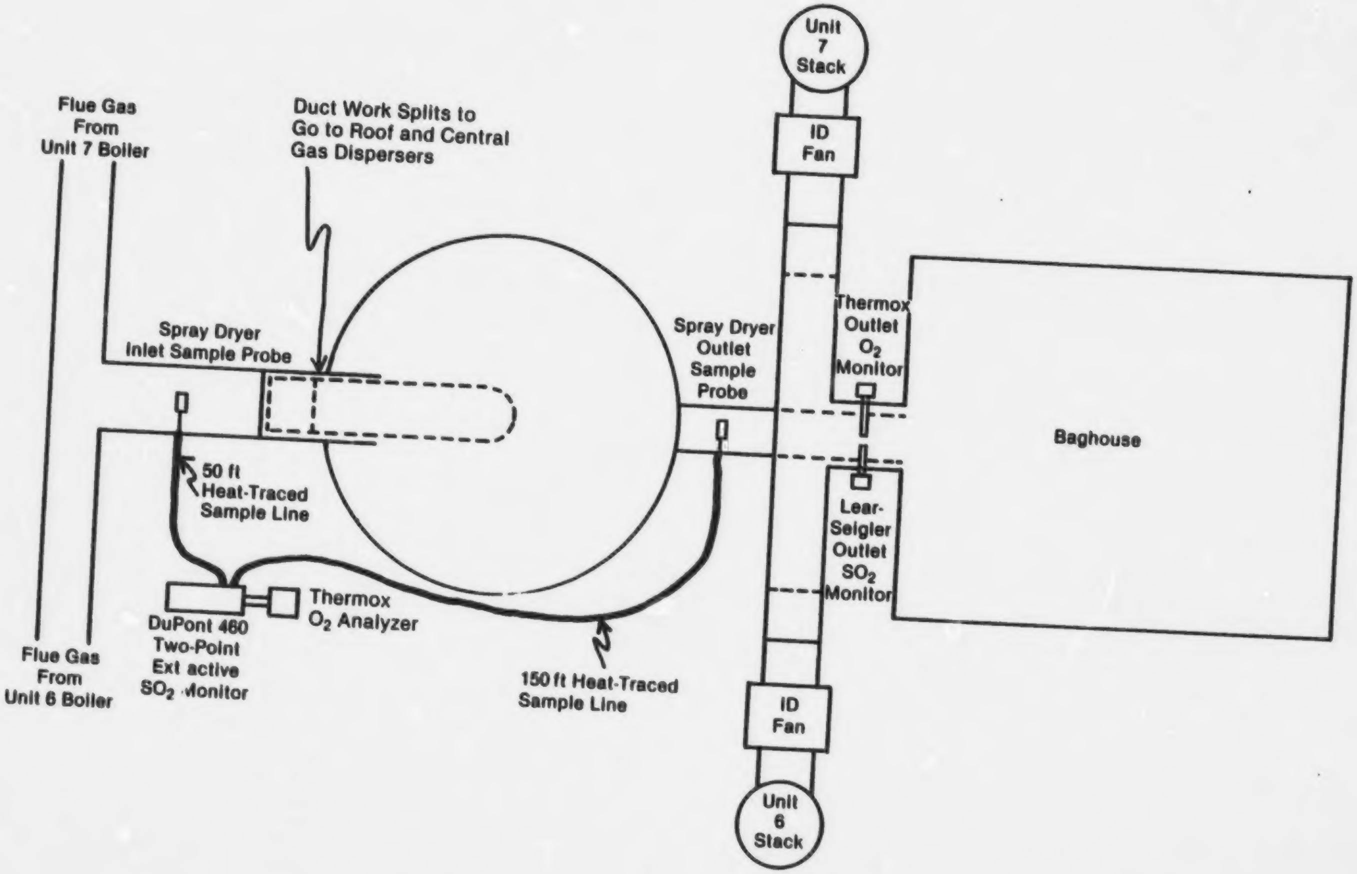
Flue Gas From Unit 7 Boiler
Duct Work Splits to Go to Roof and Central Gas Dispersers
Unit 7 Stack
ID Fan
Spray Dryer Inlet Sample Probe
Spray Dryer Outlet Sample Probe
Thermox Outlet O_2 Monitor
Baghouse
50 ft Heat-Traced Sample Line
Lear-Seigler Outlet SO_2 Monitor
Thermox O_2 Analyzer
DuPont 460 Two-Point Ext active SO_2 Monitor
Flue Gas From Unit 6 Boiler
150 ft Heat-Traced Sample Line
ID Fan
Unit 6 Stack

Figure 5-1. Top view of Riverside dry FGD system duct work showing CEM system installation.

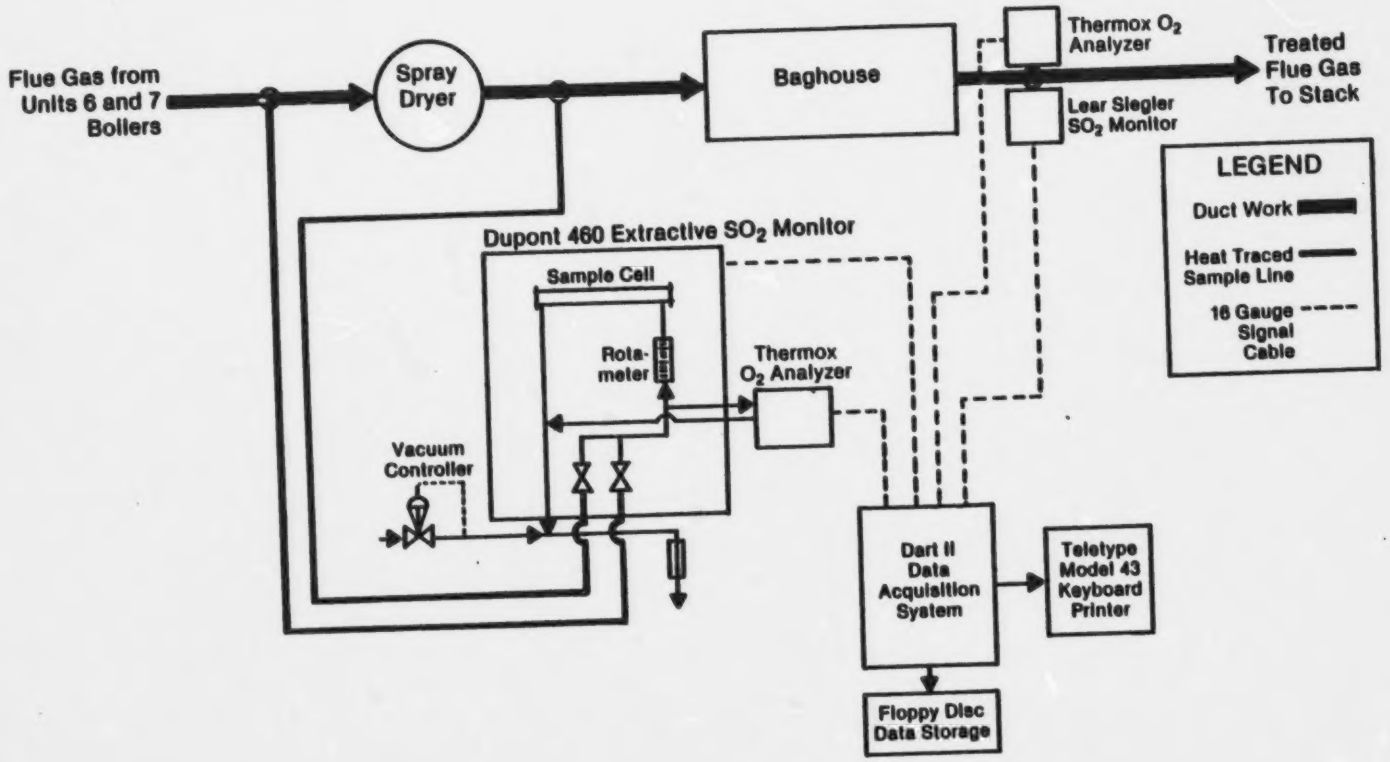
Flue Gas from
Units 6 and 7
Boilers
Spray
Dryer
Baghouse
Thermox O_2
Analyzer
Lear Siegler
SO_2 Monitor
Treated
Flue Gas
To Stack
LEGEND
Duct Work
Heat Traced
Sample Line
16 Gauge
Signal
Cable
Dupont 460 Extractive SO_2 Monitor
Sample Cell
Rota-
meter
Thermox
O_2 Analyzer
Vacuum
Controller
Dart II
Data
Acquisition
System
Teletype
Model 43
Keyboard
Printer
Floppy Disc
Data Storage

Figure 5-2. Schematic of continuous emission monitor system.

Because the spray dryer outlet location values were not used in determining system SO_2 removal, this point was not certified. However, span and zero drift checks and relative accuracy tests were periodically conducted for this sampling location.

In addition to the relative accuracy tests during the monitor certification procedures, the relative accuracy at each location was continually checked against Method 6 manual measurement results throughout the test program. The spray dryer inlet and fabric filter outlet monitoring locations continued to show very good agreement with the reference method. The spray dryer outlet monitoring occasionally disagreed with the reference method results.

Two reasons for this disagreement are apparent. First, the spray dryer outlet sample location was relatively far away from the DuPont SO_2 monitor. Consequently, a 150-foot sample line was required for the spray dryer inlet location. Also, this 150-foot sample line was constructed with 3/8-inch rather than 1/4-inch tubing. This sample line represented a significant volume of flue gas that had to be replaced before the fresh sample entered the analyzers. Also, as originally plumbed, the Thermox oxygen monitor had a much slower response time than the DuPont monitor. At the spray dryer outlet location, where significant "dead time" was required before a fresh flue gas sample made it to the analyzers, the oxygen 5-minute average values recorded for the spray dryer outlet location included erroneously high oxygen values from early in the sampling cycle for this location. Thus, the oxygen-corrected SO_2 concentrations during these periods were higher than the reference method values. The Thermox oxygen monitor interfaced with the DuPont 460 was replumbed to result in a much faster instrument response. Care was taken to edit out data from these earlier slow response time periods when calculating individual spray dryer and fabric filter contributions to overall removal.

A second reason for disagreement at this location applies only to the calcium chloride addition periods during the high sulfur test series.

During this time period, analyses of the solids collected in the fabric filter indicate that the solids leaving the spray dryer contained high residual moisture levels, and sufficient excess lime levels to effect relatively high SO_2 removal efficiencies in the fabric filter. The SO_2 removal across the fabric filter was by far the greatest during this test period. During this test period the spray dryer outlet continuous monitor response was once again much greater than the reference method measurement. However, in these tests the continuous monitor oxygen levels were at a value between those for the spray dryer inlet and fabric filter inlet locations, not significantly higher as during the slow response problem period. Consequently, it was decided that the poor agreement was due to significant SO_2 removal on the reference method sample train particulate filter surface. The continuous monitor only samples for 4-1/2 minutes per cycle; then the sample probe is cleaned with a high pressure air blowback flow. The reference method, however, collects particulate on a filter for 30 minutes at a time. It appears that the reference method particulate filter was acting like the full-scale fabric filter in effecting SO_2 removal. In fact, the reference method SO_2 concentration values for the spray dryer outlet location were very near the continuous monitoring results for the fabric filter outlet, indicating virtually identical SO_2 removal levels across each filter surface. Consequently, the continuous monitoring results for the spray dryer outlet location are taken as being more credible than the reference method values during the calcium chloride tests. Since the sample probe surface area is large relative to the sample flow and the sample flow only continues for 4 1/2 minutes, it is assumed that little or no SO_2 removal was occurring on the CEMS in-stack filter, while significant SO_2 removal occurred on the reference method particulate filter.

5.2.2 SO_2 Removal Control Software

At the time this test program began, the Honeywell process control computer on the Riverside system was set up to function as a simple PID controller varying percent lime in the atomizer feed slurry to achieve the set point SO_2 removal level. Generally, NSP operated the system by simply controlling the percent of fresh lime in the atomizer feed solids directly. In this mode, SO_2 removal could be varied by increasing or decreasing the fresh lime fraction set point.

However, Niro Atomizer had developed more sophisticated percent SO_2 removal control software for use on their commercial utility systems. The software takes into account the fact that the relationship between overall SO_2 removal and lime reagent ratio is not necessarily linear, and takes into account the slurry residence time in the mixing and feed tanks. Because it was desired for this program to operate the Riverside system more like a commercial system rather than a demonstration system, Niro retrofitted the Honeywell control computer with the more sophisticated SO_2 removal control software.

The first two weeks of the test program involved some on-site tuning of the percent removal control software to the Riverside system. Tuning was required to reshape the SO_2 removal versus lime reagent ratio relationship to more closely match the performance of the Riverside system with the low sulfur coal and to adjust the time constant for the control function to compensate for the residence time of the slurry feed system.

Minor retuning of the software was required when changing from low sulfur to high sulfur coal. Otherwise, the SO_2 removal software worked well throughout the program.

5.3 SYSTEM LIMITATIONS

The major objective of this program has been to evaluate the performance of a full-scale utility spray dryer/baghouse dry FGD system. These results are to provide meaningful input to utilities who are considering installing a similar system on a new unit, or as a retrofit to an old unit. There are several benefits to conducting this program on the Riverside system. For example, the Riverside system was the first full-scale lime-based spray dryer/baghouse FGD system in operation at a utility site available for characterization. This evaluation program would have been considerably delayed if it had been decided to conduct the program at another site. Also, the Riverside system contains only one spray dryer module and one baghouse module. A characterization of a multiple module system would have been much more complex and expensive to conduct, as simultaneous sampling on multiple modules would have been required. Finally, the Riverside Unit 6 and 7 boilers are capable of burning either low sulfur or high sulfur coals. This capability allowed the rather unique opportunity to evaluate spray dryer-based FGD performance for both low and high sulfur fuels at one test site.

However, there are some specifics about the Riverside system which limit the usefulness of some results of this evaluation. These specifics primarily center around the fact that the Riverside system is a demonstration system largely financed by the system vendor, rather than a commercial system, and that the Riverside Unit 6 and 7 boilers are in peaking service rather than baseload service. These limitations, and their impacts on the usefulness of the results from this program, are discussed below.

First, as mentioned above, Riverside Units 6 and 7 are peaking units. As such, they are rarely operated in the winter and only operate part-time during July to October. This involves operation at or near full load during daylight hours, operating at minimum load (30 to 50 MW) overnight during the week, and banking the boilers over the weekend. Figure 5-3 is an illustration of the combined Unit 6 and 7 loads during a typical week. Although the FGD system was operated at desired SO_2 removal levels 24 hours per day during the low sulfur coal tests, only about 12 hours per weekday were available for evaluating FGD system performance at full load. At the beginning of each 12-hour full-load period, the FGD system generally went through a transient period due to a large increase in boiler load. On Mondays the unit had to undergo a cold start-up. Although this cycling during the low sulfur coal tests provided a severe test of the capabilities of the system, it reduced the period of steady-state operation at the desired SO_2 removal level during which lime reagent consumption could be measured. Due to

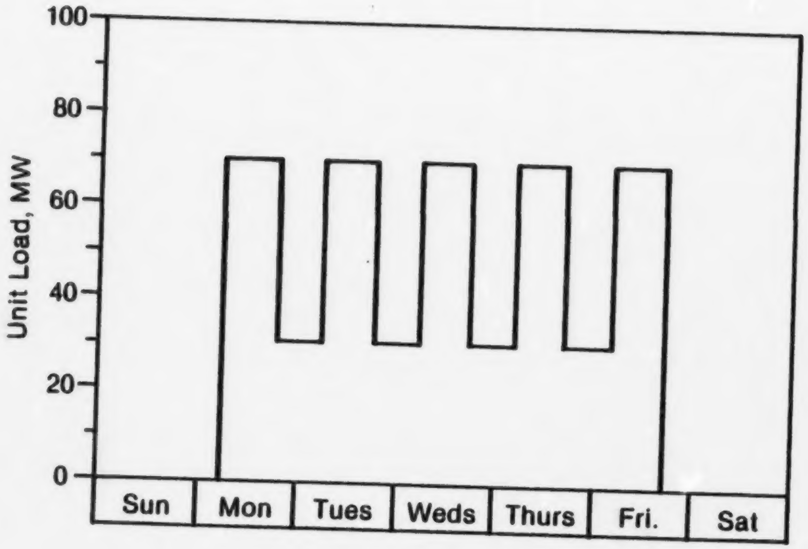

Figure 5-3. Illustration of planned boiler operation during test program.

boiler operation and FGD system constraints during the high sulfur coal tests, the unit was mostly operated at a constant load 24-hours per day from Monday morning through Friday evening.

Additionally, the Riverside system was the first utility-scale system designed and built by Joy/Niro and was built as a demonstration unit. As the first unit built, the Riverside system has provided the opportunity to refine and modify design features for subsequent systems. Thus, some specifics of the Riverside system are different from what will be found in later designs. An example of this is the slurry feed system design, which has been modified for subsequent system designs to provide quicker response to transients such as load changes. At Riverside, lime slurry, makeup water, and recycle solids are mixed in a single tank. The lime slurry addition rate is based on SO_2 removal (for the SO_2 removal control mode of operation), the makeup water rate is controlled to maintain level in the mix tank, and the recycle solids rate is controlled to achieve a set weight percent solids (normally 35 percent solids). The mix tank has a residence time of approximately 45 minutes. This slurry mixture then overflows to an atomizer feed tank with a similar residence time. When the inputs to the mix tank change composition abruptly (such as when the unit load increases), approximately 3 or 4 hours are required before the feed system stabilizes near steady state for the new conditions. Recently designed Joy/Niro systems have a faster response slurry feed system. In these systems, recycle solids and makeup water are mixed in a recycle slurry tank to a consistency of approximately 50 to 60 weight percent solids. The lime and recycle slurries are then mixed in a feed tank with a relatively short residence time of one-half hour or less.

The impacts of the slurry feed preparation system design are particularly important at the Riverside station, as the normal station operation causes significant load changes at least twice per day. In fact, on some days during this test program, the NSP dispatcher called for the unit load to be varied between 70 MW and 90 MW throughout the day. On these days, the unit never operated at one load long enough for the feed system to stabilize. On most other days, even if the load was steady all day, only 8 or 9 hours of the 12 hours of full load operation actually represented steady-state conditions.

Other aspects of the Riverside system's status as a demonstration unit affected the results of this program. For example, as mentioned above, the system contains only one spray dryer module, while most utility systems will be multiple-module systems. In a multiple-module system, equipment problems which affect one individual module have a smaller impact on overall system performance. Being a one-module system, equipment problems tended to cause the entire system to have to be shut down, or operated at conditions other than those desired. Even considering that the smaller Riverside system only warrants a single dryer vessel, some individual components of the system have not been installed with the redundancy that the vendor would likely install in a commercial system. These considerations have had a detrimental effect on both the amount of system downtime and the number of process-equipment-related upsets during the test program.

Another consideration which has affected the test program involves the recent history of the Riverside station. For nearly the first two years of operation, the FGD system was used as a full-scale demonstration and testing unit by the process vendors. During this time, the Joy/Niro joint venture had responsibility for the operation of the system, even though NSP actually provided operating personnel. Within the year prior to the test program, NSP had assumed responsibility for the operation of the FGD system. Immediately prior to the test program, the Unit 6 and 7 boilers and FGD system were off-line for much of the winter and spring, as NSP does not need power production from these units during this time. During this long period of downtime, normal personnel turnover (promotions, retirement, transfers, etc.) resulted in a number of new operators rotating into the FGD system operating staff. Early in the test program, then, the FGD system was being operated for the first time in several months with a staff of operators having little previous experience with the FGD system. Consequently, a lot of test days early in the program were not productive as far as representing steady-state operation at test conditions. As the test program continued, successful test days represented a higher fraction of potential days of operation.

A final consideration here is that, after the Joy/Niro joint venture turned over the dry FGD system to the utility, and prior to conducting this test program, NSP only operated the system at 50 to 60 percent SO_2 removal levels. For such moderate SO_2 removal levels, they had previously operated the system under very conservative conditions, such as higher spray dryer outlet temperatures. Thus, operation at 75 to 90 percent SO_2 removal, with a 20°F approach to adiabatic saturation was not a normal operating mode immediately prior to this test program. Early in the program, the operators tended to revert to higher spray dryer outlet temperatures during any minor upset, such as soot blowing in the boilers. This would move the operation away from the desired conditions and would preclude acquiring desired steady-state operating data. As the program continued though, this occurred much less frequently as the operators became more comfortable with operating at test conditions.

Section 6, System Operation, describes some of the recurring problems which limited the amount of steady-state operating data collected during this program. The discussions in that section also address the amount of operating time lost to these problems. However, because of the Riverside system's unique status of being a demonstration unit and being installed on peaking boilers, system availability was not strictly evaluated. It was felt that availability information for this system would be relatively meaningless for most commercial systems.

5.4 REFERENCES

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SECTION 6

SYSTEM OPERATION

The most obvious technical question regarding the characterization of an operating spray dryer-based FGD system is how well it performs with respect to SO_2 removal, particulate removal, etc. These technical issues are discussed in Section 7, Emission Control Performance. An issue of equal importance to utilities planning such a system is how well it operates. A major selling point of spray dryer-based dry FGD systems has been the reputed simplicity of the systems relative to wet scrubbing FGD systems. The characterization of the Riverside system offers the opportunity to determine whether in fact spray dryer-based systems are simple to operate.

As described in Section 5, Test Program Description, the Riverside system is not the best to evaluate the operation of a utility spray dryer-based FGD system. The Riverside system has several limitations as a test site, including the fact that it is the system vendors' first full-scale installation, it was designed as a demonstration system rather than a turnkey commercial system, and it is installed on peaking boilers. Many of the problems observed at the Riverside system during this test program can be attributed to these limitations. These problems were mentioned in Section 5 and will not be discussed in detail here. However, several operational problems appear to be general in nature and will be discussed in this section.

This section is divided into two subsections. The first is an overview of how the system operated. Both positive and negative aspects of the operation of the Riverside system are discussed. Included are both site-specific and more general problems observed at the Riverside system during this test program. Although not all of these problems are discussed in detail, it is worthwhile that they be mentioned so that the same problems may be avoided in later systems. The second subsection is a discussion of the system operation problems that appear to be generic to spray dryer-based FGD systems, or at least problems that could likely be encountered on similar utility systems. Each problem area is described and potential solutions are briefly discussed.

6.1 SYSTEM OPERATION OVERVIEW

In general, the system operated well during the test program. As described in subsection 5.2, System Limitations, there were problems, particularly early in the program. Many of these problems were related to several factors: the system had not been operated much in the months prior to the beginning of the test program, many of the operators had little experience operating the system, and the test conditions of 75 to 90 percent removal levels and 20°F approach to saturation based on the fabric filter outlet adiabatic saturation temperature were less conservative than their normal operating conditions.

Early in the program, problems encountered were related to the fact that the control system had not previously been equipped to control SO_2 removal. Approximately 2 weeks were required to install and tune the percent SO_2 removal control software, sort out a variety of minor problems related to operating the unit again after its infrequent operation in the previous months, and complete certification of the CEMS.

After this 2-week debugging period, all 5 days of the third week saw successful operation at 75 percent SO_2 removal and a nominal 2:1 air-to-cloth ratio. During the remaining 5 weeks of the low sulfur test program, another 11 days of potential run data were lost due to the unit being off line or off of desired operating conditions. On several other days, a few hours of potential run data were lost. The problems included:

- Recycle System Problems--Three test days were lost due to loss of recycle solids flow to the mix tank. These problems included the recycle silo rotary valve jamming, recycle blow pots out of service, and solids conveyors out of service. On two other test days, a few hours of data were lost, due to tramp metal materials jamming the rotary valve at the bottom of the recycle solids bin. In each of the instances, the FGD system remained on line, but the system reverted to once-through operation as recycle flow was lost. Also, as the percent solids content in the atomizer feed slurry began to fall when the flow of recycle solid was interrupted, the FGD system operating practice called for the approach to adiabatic saturation to be raised to 30°F or 40°F, depending on the solids level. If the SO_2 removal setpoint was maintained during these periods, the process control computer called for much higher lime addition rates to compensate for once-through operation and higher outlet temperatures. In some instances, the lime feed rate was instead manually held at normal pre-upset levels, allowing SO_2 removal to be reduced significantly.

- Slurry Feed Problems--These included buildup of solids on mix tank or atomizer feed tank walls, and/or plugged suction lines for the mix tank transfer pumps or the atomizer feed pumps. These problems occurred on six occasions. Three occasions each caused an entire day of data to be lost, while three more involved the loss of several hours of data. In general, these problems caused the FGD system to be brought off line for repairs.

- Atomizer Problems--Two days were lost due to atomizer downtime. In one instance, the atomizer was restarted in spite of several serious alarms when loose electrical connections prevented the lubrication oil circulating pump from operating. Damage to the atomizer gearbox occurred in this instance. The second instance involved full slurry flow to the atomizer wheel while the atomizer was off line, allowing slurry to flow up the spindle to which the wheel is attached and contaminate the lubricating oil in the lower gearbox sump. Following this incident, the lube oil sump was cleaned out and the atomizer was placed back in service.

- Ball Mill Slaker Problems--One test day and a portion of another were lost due to ball mill slaker feed pluggage while attempting to conduct the ball mill-slaked lime test conditions. Because ball mill slaker feed problems could not quickly be resolved, these test conditions were never successfully run.

- Miscellaneous Problems--One test day was lost when the FGD system had to be brought off line after an FGD system operator spilled a soft drink into the keyboard for the Honeywell process control computer. With this keyboard out of service, operator interface with the supervisory station of the process control computer was not possible. The system had been operated 2 weeks earlier with the supervisory station out of service with a hardware problem. The supervisory control software has many system protection interlocks that are not included in the basic control software on this system. It was during this previous period when the supervisory control station was out of service that the atomizer damage occurred. As mentioned, the atomizer was restarted when the lubricating oil recirculation pump was not running, in spite of several serious alarms. In order to avoid another incidence of atomizer damage while running without interlocks, the unit was brought down when keyboard damage disabled the supervisory control station.

  Another miscellaneous problem involved a loss of one day of data when the 2.7:1 air-to-cloth ratio test called for in the original test plan was attempted, and a combination of events caused the fabric filter emergency bypass to open. The specific cause of this incident is more related to conducting this test program than indicating how the unit operates, so the incident will not be further discussed.

The first four specific problems above appear to be general problems that could occur on virtually any spray dryer-based FGD system. These problem areas are further discussed in subsection 6.2. The miscellaneous problems appear to be site-specific and are not discussed further.

During the high sulfur coal test period, the FGD system generally operated very well. The high sulfur test period involved 26 weekdays of potential full load operation. One day was lost as the coal feed bin composition changed from low sulfur to high sulfur coal conditions and fluctuating sulfur levels were encountered. Another five days were lost when the entire FGD system and boilers were brought off line to repair a failed expansion joint on the baghouse reverse gas duct work. Two more days were lost due to unplanned boiler outages unrelated to the FGD system. Finally, a day was lost as operation of the ball mill slaker was once again attempted, and lime feed screw pluggage was again encountered. These problems resulted in 9 days of the 26 potential days of high sulfur operation being lost. All but the one day lost during the ball mill slaking attempts were due to problems not directly related to the FGD system. Actually, that day of lost data was a result of the test program being conducted, as normal operation at Riverside would not call for ball mill slaker operation.

Otherwise, only a few hours of data at a time were lost due to operating problems. These operating problems included:

- plugged blow pots and fabric filter conveyor problems causing a loss of recycle solids flow. As described above for low sulfur coal operation, the loss of recycle solids flow caused the unit to approach once-through operation and required that the spray dryer outlet temperatures be increased.

- another incident where feed slurry was pumped to a standing atomizer wheel, contaminating the oil in the lower lubricating oil sump. This required that the unit be shut down long enough to clean this lower sump and replace the lubricating oil.

- loss of lime feed for several hours due to a failed gasket on the lime feed bin. During this period, SO_2 removal fell to very low levels, as only alkalinity in the recycle solids was available for SO_2 removal.

The first two operating problems are discussed further in the following subsections. The third appears to be an isolated incident that bears no further discussion.

One point that was obvious from observing the operation of this system is that many of the problems originally anticipated for spray dryer-based FGD systems were not observed. For example, buildup of wet solids on spray dryer vessel walls did not appear to occur. Some buildup of solids on spray dryer walls was observed, particularly in a ring around the straight-sided wall of the vessel approximately where the atomized slurry halo would project over to the wall. However, this buildup of no greater than 2 or 3 inches thickness appeared to be a steady-state condition. The buildup neither increased nor subsided throughout the 3-month duration of this test program. Otherwise, the vessel walls were only lightly dusted with dry solids.

In all cases, the solids dropping out of the spray dryer and solids collected in the fabric filter remained dry and free-flowing. During the low sulfur coal test period, the spray dryer dropout solids varied from 0.1 to 0.4 weight percent excess moisture. Fabric filter solids moisture levels varied from 0.1 to 0.3 weight percent. During the baseline high sulfur coal tests, spray dryer dropout solids moisture levels varied from 0.6 to 1.3 percent, and fabric filter solids moisture levels ranged from 0.2 to 0.9 percent. It is not obvious why the values measured in the high sulfur tests increased above those values measured during the low sulfur tests, other than the fact that a different coal ash was involved and that the spray dried solids contained a higher fraction of calcium sulfite/sulfate salts and excess lime.

Even during the calcium chloride addition tests, no problems with wet solids were encountered. The effect of calcium chloride addition was expected to prolong droplet drying times in the dryer and to increase residual moisture levels in the solids collected in the fabric filter. These effects apparently did occur, as spray dryer solids moisture levels were increased to 0.9 to 2.4 percent and fabric filter moisture levels were increased to 0.5 to 1.8 percent. In spite of continuing to operate the spray dryer at approximately an 18°F approach to adiabatic saturation based on the estimated spray dryer inlet wet bulb temperature during the calcium chloride tests, spray dryer dropout solids moisture levels remained below 3 percent and the solids remained free flowing. Fabric filter solids moisture levels were essentially doubled by adding calcium chloride, but these solids also remained free flowing.

Even during upset conditions, spray dryer and baghouse problems did not result. In two instances, full atomizer feed slurry flow was fed to a standing (non-rotating) atomizer wheel. In each case the overflowing slurry fell to the bottom of the spray dryer vessel, overflowed out the double tipping valves, and spilled on the floor below the dryer vessel. The only dryer vessel problem resulting from these upsets was a minor buildup of dried solids on the vanes of the central gas disperser directly below the atomizer wheel. Because slurry/flue gas contact was obviously poor with the atomizer wheel not spinning, the flue gas leaving the spray dryer vessel during these upsets was hot and dry. The fabric filter was totally unaffected by these upsets.

In general, the baghouse operated quite well throughout the program. As mentioned above, when attempting to operate the baghouse at a 2.7:1 air-to-cloth ratio, a series of events led to the baghouse emergency bypass opening, sending 15 grain/dscf flue gas directly to the unit stacks. However, this problem was the result of an attempt to operate the baghouse outside its range of design conditions specifically for this test program. Long-term effects such as the impacts of the upstream spray dryer on bag life or on corrosion on compartment walls could not be evaluated in this 3-month test program.

6.2 DISCUSSION OF OPERATING PROBLEMS

In the previous subsection, a number of site-specific problems were identified that do not warrant further discussion. However, four problem areas affected the unit operation continually. The problems conceivably could be encountered in any similar spray dryer-based system. Each of these problem areas--the slurry feed system, the ash handling system, the ball mill slaker, and the atomizer protection system--are discussed below.

6.2.1 Slurry Feed System

In a recycle lime system, lime slurries containing up to 25 percent solids and recycle/lime slurries of 30 to 40 percent solids are commonly encountered. When dealing with slurries with a high solids content and high viscosity, problems such as plugging of pump suction lines, solids buildup on tank walls, plugging of in-line screens used to remove oversized material, and loss of flow when switching pumps are commonly encountered. Such problems were encountered often at the Riverside system. Years of operation of wet lime/limestone FGD systems have established means of dealing with such problems: always keep slurry in tanks well agitated, always maintain slurry levels above the agitator blade level, never allow slurry to stand in lines, provide for on-line changing of plugged or partially plugged screens, etc. These same solutions will need to be applied in spray drying systems.

The quantities of these slurries that must be dealt with in a spray dryer system are much smaller than what would be encountered in a wet system. At Riverside, typical atomizer feed slurry rates are 150 to

200 gpm. In a similarly sized limestone wet FGD system, the slurry recirculation rate could be as high as 40,000 gpm. The point to be made is that while some of the slurry handling problems of a wet FGD system may still be encountered in a spray dryer system, they will occur on a greatly reduced size of equipment. This should make both problem solving and routine maintenance easier. Another important point to be noted is that no chemical scaling tendencies were observed at Riverside.

6.2.2 Ash Handling System

In comparing wet and dry FGD systems, the spray dryer system has a slurry feed system that deals with much lower flow rates for a given unit capacity, but the quantities of dry ash and FGD by-products that must be moved around the system are substantially greater than for a comparably sized particulate collection device/wet scrubber system.

For example, at Riverside the amount of solids entrained in the flue gas at the fabric filter inlet (spray dryer outlet) is 3 to 5 times that in the spray dryer inlet gas. For low sulfur coal operation, only a small portion of this increase is attributable to the lime reagent introduced and SO_2 removed in the spray dryer. The majority is material being recycled from the fabric filter catch to the spray dryer. Thus, the rate at which solids are removed from the fabric filter hoppers and transported to recycle storage bins can be several times greater than the net rate of waste product actually leaving the system.

Specifically, for low sulfur coal, 75 percent SO_2 removal, and unit operation at 80 MW, the steady state rate of fly ash and spray dryer by-products leaving the system amounted to 7 to 8 tons/hr. However, due to the effects of recycle, approximately 20 tons/hr were actually being collected by the baghouse. The 12 to 13 tons/hr excess between that going to the disposal silo and the 20 tons/hr being collected was being recycled to the slurry feed system. In this example, roughly three times the quantity of fly ash and spray dryer solids leaving the system must be continually removed from the baghouse hoppers, and roughly twice the quantity leaving the system must be continually transported to the recycle storage bin.

At Riverside, solids collected in the baghouse hoppers and at the bottom of the spray dryer are intermittently dumped onto mechanical conveyors through motor-driven tipping valves. One conveyor each handles ash from the six compartments on the north and south sides of the baghouse, respectively, while a third conveyor handles spray dryer bottom solids. These conveyors empty into surge bins mounted above air conveying blow pots. The blow pots cycle through the following five consecutive processes: filling from the surge bin, isolation from the surge bin, pressurization, pneumatic conveying to either the recycle or disposal storage silos, and then depressurization. The recycle silo empties through a rotary valve onto a weigh belt which meters recycle material into the mix tank.

The problems with solids handling which most frequently occurred at Riverside involved the baghouse mechanical conveyors, blow pots, and the recycle bin rotary valve. The problems with the mechanical conveyors appeared to be related to marginal capacity. The north or south conveyors frequently tripped out because their drive motors were overloaded. Momentary overloading of the conveyors is caused by the nature of the operation of the baghouse, where compartments clean intermittently throughout each hour. That is, the average rate at which the baghouse collects material might be 20 tons/hr if the same number of compartments were on-line on both sides. However, this average is a composite of short periods of high solids flow, immediately after a cleaning compartment begins reverse gas flow, tapering off to very low solids flow rates as the hopper below the cleaned compartment empties. Thus, one conveyor may see instantaneous rates as high as several times 10 tons/hr and as low as zero. This problem was apparently corrected after this test program was completed by a modification which slows the rate at which ash/spray dryer by-products are emptied from the hoppers onto the conveyor. This modification reduces the maximum solids rate seen by the conveyors by causing the hopper to empty onto the conveyers at a more controlled rate.

In addition, the conveyors require occasional maintenance, such as replacement of failed drive motors and bearings. If one conveyor must be off-line for a very long time, then all six of the compartments emptied by that conveyor must be taken off-line once the hoppers below those compartments are full of ash. At Riverside, failure of one conveyor can cause the boiler load to be limited to that which can be handled by the six compartments remaining on-line. Because the rate at which solids are collected in a fabric filter downstream of a spray dryer is greatly increased, unless the hoppers are increased in size compared to conventional particulate control configurations, such a conveyor failure can very quickly limit unit load.

Failure of a blow pot can have a similar effect, as only a small surge bin separates each conveyor from a blow pot. NSP has attempted to provide some redundancy in blow pots, but in an instance where only one blow pot is available to accept solids from a conveyor, a blow pot outage can cause the conveyor to be shut down as well. Common blow pot failures observed included plugging, leaking isolation valves, and loss of air pressure to the pneumatically operated valves. Blow pot operation is of particular importance in pneumatic systems such as the dense phase system at Riverside where one transfer vessel services several hoppers (in this case six fabric filter compartments or half of the fabric filter). Other pneumatic systems may use one small transfer vessel per hopper, or some systems may use strictly mechanical conveying. Of course these alternate arrangements can have critical equipment as well that can limit system capacity on failure.

A third piece of solids handling equipment which rapidly affected the operation of the system on failure was the rotary valve at the bottom of the recycle solids bin. When this valve failed, often due to a piece of tramp material jamming the blades, the solids content in the atomizer feed slurry immediately began to drop, and the system began to approach once-through lime operation. The large slurry mix tank and atomizer feed tank could be considered a 1.5 hour reservoir of feed slurry, but in order to avoid splashing slurry on tank walls and a resulting buildup of dry solids, the tanks must be continually kept near full. Consequently, these tanks begin to dilute immediately when recycle solids flow is interrupted because makeup water must be added to maintain level.

The solids handling equipment appears to be a key to successful operation of the spray dryer/baghouse system. The individual pieces of equipment must be sized to handle solids rates much higher than is typical for conventional particulate removal alone.

6.2.3 Ball Mill Slaker

As mentioned previously, during this program the ball mill slaker did not operate successfully for any extended period. The feed end of the slaker tended to plug with wet lime solids. While there are several possible reasons why the plugging continually occurred, the actual cause was not identified. The ball mill operation is discussed below.

The ball mill slaker is fed by an independently driven screw feeder inserted directly through the trunnion bearing of the mill. Product lime flows out the opposite end, through a cylindrical screen, and into a product collection trough. Figure 6-1 is a simplified cross section of the ball mill depicting the feed and product ends of the mill. Two things are clear from this simplified illustration: first, vapors produced by the heat of the slaking reaction can only leave the slaker with the product or flow back through the feed end. Secondly, little hydraulic head is available to promote the flow of the viscous slaked lime slurry out the product end of the slaker without immersing the feed screw in slurry.

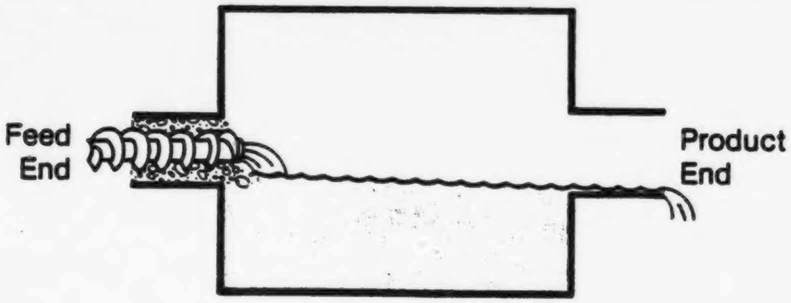

Figure 6-1. Simplified cross section of ball mill slaker

Either of these considerations may have contributed to feed screw pluggage. The ball mill slaker was operated at a very low water-to-lime ratio, resulting in 30 to 35 percent solids in the mill product slurry and a product temperature of 97°C (207°F) or greater. At these conditions, the product slurry is very viscous, having a paste-like consistency. Also, with the product slurry very near or perhaps actually boiling, vapor production rates are high. Both of these effects of low water-lime ratio can promote feed screw pluggage. Another consideration is that the ball mill slaker had not been operated for some time prior to this test program, as NSP prefers to operate the attrition slaker at Riverside. The mill had not been completely cleaned out after its last use, and solids buildup around the discharge end undoubtedly contributed to the slurry level in the mill backing up into the screw feeder.

A final problem specific to the Riverside system may also have contributed to feed screw pluggage. The SO_2 removal software in the process control computer tended to adjust the lime slurry makeup rate to the mix tank after a major change in the process (e.g., unit load change) in a classic dampened controller response. That is, after an abrupt process change the lime slurry makeup rate to the mix tank would tend to overshoot and then undershoot for several cycles before stabilizing at the required value. During the undershoot portion of the response, the lime slurry feed rates might be completely stopped. As the Riverside system has little lime slurry storage capacity, the slaking rate tended to directly follow the slurry makeup rate. Thus, periods of high slaking rates would be followed abruptly by periods where the screw feeder would shut down. Shutting down the screw feeder momentarily several times in succession undoubtedly contributed to the plugging problems.

The ball mill slaker problems at Riverside appear to be somewhat site-specific as ball mill slakers have operated successfully elsewhere (1,2). In retrospect, the slaker might have run more successfully at a higher water-to-lime ratio, resulting in a less viscous product slurry and less vapor release. However, in the attempts to run the ball mill slaker during the high sulfur tests in particular, the slaking water piping size did not allow operation at a higher water-to-lime ratio for the lime slaking rates required. During the high sulfur coal tests, lime slaking rates averaged approximately four times those required for the normal low sulfur fuel at similar unit load and percent SO_2 removal conditions.

The slaker control scheme sets the water-to-lime ratio in the slaker based on quicklime weigh belt measurements and makeup water orifice flow rate measurements. Neither the control computer nor the FGD system operator has any indication of the slaked lime temperature as it exits the ball mill slaker. These ball mill slaker tests may have been more successful had a readout of ball mill exit temperature been available. The ball mill water-to-lime ratio set point could have been raised to achieve a lower outlet temperature than the near boiling conditions that apparently resulted, particularly in the low sulfur coal tests.

6.2.4 Atomizer Problems

Although the atomizer motor, gearbox, and nozzle wheel were generally trouble-free, on several occasions a problem which could result in atomizer damage was observed.

Two scenarios for potential damage were observed. One occurred when the unit was forced to run from the basic, or less sophisticated, control station of the computer control system while the more sophisticated supervisory station was undergoing repair. The control software at Riverside does not have full interlock portection for the atomizer when running from the basic station. Interlocks are software which automatically shut down the atomizer when given inputs that are indicators of problems which might result in damage to the atomizer. While running in this mode, a minor problem involving loose wires to the atomizer oil circulating pump occurred, intermittently shutting the pump off. However, the basic station only gave the control operator an alarm rather than shutting the atomizer down automatically. The atomizer continued to run for several minutes without oil circulation and sustained gearbox damage.

This incident may be very site-specific to the Riverside system due to the limitations discussed earlier. First, Joy/Niro has reported that their commercial systems have full atomizer interlock protection in both the supervisory and basic computer control stations. Second, an operating staff with more experience on a spray dryer system might have shut down the atomizer more quickly when given an indication of a loss of oil flow and would not have attempted to restart the machine prior to remedial action.

The second scenario which could result in atomizer damage was observed on more than one occasion. This incident involved feeding slurry to the atomizer wheel when it was not rotating. Since the non-rotating wheel has a much lower hydraulic capacity than a rotating wheel, slurry fed to the standing wheel tends to overflow the wheel and can flow up the spindle to which the wheel is attached and enter the atomizer oil system. In such instances the oil sump can be immediately emptied and flushed to avoid damage, but if the atomizer is operated before cleaning, the slurry in the oil can eventually cause gearbox damage.

Such an instance of feeding slurry to a standing wheel can occur from operator error in establishing flow to the atomizer when it is not in operation and/or starting the atomizer from the basic station without full interlock protection. As for the previous discussion, such an occurrence is much less likely for a commercial Joy/Niro system, as even the basic station would have a full interlock protection. The interlock system would normally close a slurry feed block valve before the atomizer shut down and would not allow this valve to open until the atomizer had returned to operation at full speed.

Since these incidents occurred, the Riverside station has retrofitted an electromechanical interlock system independent of the Honeywell process control computer.

However, even with a properly operating interlock system, the previously described problem could occur. One such event occurred during this test program. In this instance, during an atomizer trip, valve seat damage prevented the atomizer feed slurry block valve from closing. In this case, all of the interlocks operated properly, but a mechanical problem allowed continued slurry flow to the standing wheel. An alert operator could catch such a problem very quickly by monitoring feed slurry flow rate and feed tank level, but it is still likely that slurry would get into the atomizer lube oil unless the flow was stopped immediately. If this type of problem should occur, the operator must respect the potential for atomizer damage and not attempt to re-start the atomizer until the lubricating system is inspected.

6.3 REFERENCES

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SECTION 7

EMISSION CONTROL PERFORMANCE

During the on-site test program, a number of aspects of the emission control capabilities for the system were measured. These include SO_2 removal, sulfur acid (gas phase SO_3) removal, and particulate emission control. Subsection 7.1 discusses the SO_2 removal capabilities of the system in both low sulfur and high sulfur coal operation.

Subsection 7.2 discusses sulfuric acid (SO_3) removal across the system. Few data are presented for the low sulfur coal conditions as suspected measurement difficulties common in low sulfur coal, alkaline ash installations prevented detection of measurable quantities of SO_3 at any point in the system. Results of several measurements are presented for the high sulfur tests.

Subsection 7.3 presents particulate removal and emission rate data for each low and high sulfur coal test condition. Data presented include grain loadings at the spray dryer inlet, spray dryer outlet/fabric filter inlet, and fabric filter outlet; particulate removal efficiency across the fabric filter; and particulate emission rates in $lb/10^6$ Btu. No particulate size distribution measurements were made during this program.

7.1 SO_2 REMOVAL PERFORMANCE

As described above, SO_2 removal performance was quantified for both low sulfur and high sulfur coal operating conditions. The following subsection is divided into separate discussions of low sulfur and high sulfur coal results.

7.1.1 SO_2 Removal During Low Sulfur Operation

The low sulfur portion of the program was divided among three separate test conditions: 75 percent removal set point at a nominal 2:1 air-to-cloth ratio in the fabric filter, 75 percent removal set point at a higher 2.2:1 to 2.3:1 nominal air-to-cloth ratio, and 90 percent removal set point at the normal 2:1 air-to-cloth ratio.

The low sulfur coal is actually a mixture of low sulfur (Sarpy Creek) subbituminous coal and a high sulfur coke. The Sarpy Creek coal reportedly has a nominal heating value of 8600 Btu/lb and a nominal sulfur content of 0.7 percent. The coke has a reported heating value of 14,100 Btu/lb and a nominal 4.5 percent sulfur content. The two are mixed on site as a blend of 88-weight percent Sarpy Creek coal and 12-weight percent high sulfur coke. The calculated heating value of this mixture is nominally 9300 Btu/lb, and the sulfur content is 1.2 percent. Three spot coal samples were collected at the boiler coal pulverizer feeders during the low sulfur test program. Analyses of the samples are summarized in Table 7-1. These analyses showed heating values of 8695 to 9185 Btu/lb. Sulfur content values for the three samples were measured at 1.07, 1.52, and 2.20 percent on an as-received basis. The wide variation in sulfur content in the grab samples is apparently an indication of poor mixing of the coals or of segregation of the vastly different coals in the mixture, either in the bunkers or within the samples collected. Combustion calculations indicate that values of 1.1 to 1.3 percent sulfur more likely represent the sulfur content for the overall mixture during these tests. This range of sulfur content values results in calculated flue gas concentrations of 800 to 1000 ppm at 7.5 to 8.0 percent oxygen, which represents the normal range of flue gas SO_2 concentration and oxygen content at the spray dryer inlet during the low sulfur tests.

TABLE 7-1. SUMMARY OF LOW SULFUR COAL ANALYSES

Ultimate Analysis (wt %)[a]	Sample 1	Sample 2	Sample 3
Moisture	22.77	21.96	21.66
Carbon	52.47	52.79	51.01
Hydrogen	3.26	3.29	3.27
Nitrogen	0.66	0.63	0.63
Sulfur	2.20	1.52	1.07
Ash	10.29	10.61	12.57
Oxygen[b]	8.35	9.20	9.79
Higher Heating Value (Btu/lb)[a]	9098	9185	8695
Elemental Analysis of Ash (wt %)			
SiO_2	30.43	34.92	31.67
Al_2O_3	14.43	15.38	14.54
TiO_2	0.57	0.56	0.58
Fe_2O_3	17.55	9.38	3.97
CaO	14.30	15.71	26.40
MgO	2.55	2.05	1.78
Na_2O	1.20	2.24	1.92
K_2O	0.62	1.13	1.28
P_2O_5	0.23	0.40	0.30
SO_3	17.87	18.48	15.44
TOTAL	99.75	100.25	97.88

[a] As received basis

[b] By difference

Table 7-2 summarizes the SO_2 removal results for the 75 percent removal set point, nominal 2:1 air-to-cloth ratio tests. The results represent the average of 40 hours of operation during this phase of the test program when the system was at "steady-state" conditions. These 40 hours of data were acquired in 5 days of 12 hours per day full load operation. For the purposes of this discussion, steady state refers to unit operation with the SO_2 control point at 75 percent removal, the approach to saturation set at 20°F (based on adiabatic saturation measured at the fabric filter outlet), and the atomizer feed solids level near 30 percent or greater.

The unit was operated at this first set of conditions for three weeks, although the first two weeks were essentially lost due to delays in successful certification of the Lear-Siegler SO_2 monitor at the fabric filter outlet and a variety of minor FGD system problems. Thus, only one week of 75 percent removal set point, nominal 2:1 air-to-cloth operation is represented in these data. The 39 to 40 hours of "steady-state" data represent reasonable capture for the approximately 60 hours the unit was at normal load (5 days x 12 hours per day).

For many hours of data, the unit was most likely not at true steady state with respect to recycle solids composition, particularly for several hours after the unit load was increased each morning. Given the cyclic nature of the boiler load, as discussed in previous sections, very few hours of operation actually represented true steady-state operation. However, the effects of the operating conditions such as approach temperature and atomizer feed solids levels are considered to have a more significant impact on system performance than minor variations in recycle solids composition.

The SO_2 removal results in Table 7-2 are based on continuous emission monitor results for the spray dryer inlet and fabric filter outlet locations. Flue gas SO_2 concentrations were corrected for air in-leakage, as indicated by the Thermox O_2 monitors, and for moisture added in the spray dryer. The amount of moisture added in the spray dryer was calculated from the atomizer feed slurry flow rate and moisture content.

TABLE 7-2. TEST RESULTS FOR THE 75% SO_2 REMOVAL SET POINT, NOMINAL 2:1 AIR-TO-CLOTH RATIO TESTS FOR LOW SULFUR COAL CONDITIONS

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	74.3	3.4	39
Reagent Ratio	0.71	0.19	40
Test Conditions			
Spray Dryer Inlet Temperature (°F)	329	7	40
Approach to Adiabatic Saturation (°F)	20[a]	0.8	40
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	429×10^3	48×10^3	40
Percent of Design Flue Gas Flow Rate	86	9.6	40
Solids in Atomizer Feed Slurry (weight percent)	29	1.2	40
Recycle Ratio	12.5:1	3.5:1	40
Relative Accuracy of Energy Balances (percent)	-0.9	2.5	40
Flue Gas Residence Time in Spray Dryer Vessel (sec)	14	-	40

[a] Based on adiabatic saturation temperature measured at the fabric filter outlet

The results show that for an average SO_2 removal of 74.3 percent, a reagent ratio of 0.71 was required. In this report, the term reagent ratio corresponds to the term stoichiometric ratio commonly used in dry FGD technology. Reagent ratio is defined by the following equation:

$$\text{Reagent Ratio} = \frac{\text{Fresh } Ca(OH)_2 \text{ in atomizer feed, lb-mole}}{SO_2 \text{ in spray dryer inlet flue gas, lb-mole}} \qquad (7\text{-}1)$$

This reagent ratio shows that slightly sub-stoichiometric amounts of lime were required to achieve the average SO_2 removal shown. This is attributed to the alkalinity in the Sarpy Creek coal ash. The three spot coal sample analyses summarized in Table 7-1 show ash compositions with 19 to 31 percent alkaline species ($CaO + M_gO + Na_2O + K_2O$). Again, the highest value corresponds to the sample with the sulfur content closest to that expected for the actual mixture, while the two lower values (19 and 21 percent) correspond to the samples with higher than expected sulfur levels. These results indicate that the ash for the overall mixture is closer to 30 percent by weight alkaline species. The reactivity of these alkaline species in the spray dryer is difficult to evaluate, but very little ash alkalinity would have to react with flue gas SO_2 to explain the sub-stoichiometric lime addition rates observed.

The reagent ratio calculations were based on three different approaches to measuring lime addition rates. The value in Table 7-2 is based on the lime addition rate as quantified by the slaked lime solids content and flow rate into the mix tank. Because of the residence times in the mix tank and atomizer feed tank, the rate that lime is made up to the mix tank does not directly correspond to the rate at which lime is being introduced at the spray dryer at that instant, but averaged over time these residence time errors are minimal.

The second method of quantifying lime addition rates is based on the mass rate reading from the weigh belt feeding quicklime to the lime slaker and the ASTM Available Lime Index for the quicklime. The third method is to calculate the fresh lime fraction of the atomizer feed slurry solids and use the product of this lime fraction and the atomizer feed rate. The fresh lime content is calculated by solving simultaneous sulfur and calcium balances on the atomizer feed slurry, using the analytical results for calcium and sulfur concentrations in the atomizer feed slurry solids, recycle solids, and fresh lime solids.

The first method, based on the lime slurry feed rate is considered the most accurate, although it requires frequent measurement of the lime slurry solids content and specific gravity. The quicklime feed weigh belt was observed to have a small positive zero offset and was determined to read low at higher feed rates during the high sulfur coal tests. Thus, the accuracy of this device in measuring lime make-up rates was suspect. The third method, based on the atomizer feed composition, can be relatively accurate. However, for low sulfur coal operation and 30 percent solids in the atomizer feed slurry, the feed slurry solids are over 90 percent recycle solids and less than 10 percent lime. Thus, minor analytical variations in the recycle solids and atomizer feed slurry solids can greatly affect the calculated lime fraction, as it is assumed to account for all differences between the two compositions. Also, the recycle solids sample is taken as it is added to the mix tank, and the recycle solids in the atomizer feed slurry represent solids added perhaps 30 minutes to one hour earlier.

Table 7-3 presents the results of reagent ratio calculations employing each of the three methods for measuring lime addition rates. The three approaches agree within 0.1 reagent ratio value, indicating a great deal of confidence that the actual value falls within this range. Note that these three methods involve entirely independent flow rate measurements and predominantly independent chemical analyses. Also note that the first two values show relatively large standard deviations. These large standard deviations result from the wide fluctuations in quicklime slaking and lime

TABLE 7-3. COMPARISON OF THREE APPROACHES TO CALCULATING REAGENT RATIOS FOR THE 75% REMOVAL, LOW SULFUR COAL CONDITIONS

Lime Addition Rate Measurement Approach	Mean Reagent Ratio Value[a]	Standard Deviation
1. Based on lime slurry solids content and feed rate	0.71	0.19
2. Based on quicklime weigh belt rates	0.64	0.18
3. Based on atomizer feed solids analyzer, atomizer feed rate	0.64	0.04

[a] Arithmetic mean of values calculated by each method for all 40 hours of test data for this set of operating conditions.

slurry feed rates as the system SO_2 control scheme reacts. The third value represents the lime feed rate as measured in the atomizer feed slurry. Changes in this rate with time are dampened by the relatively long slurry residence times in the atomizer feed preparation system. Consequently, the standard deviation for the third value in Table 7-3 is much lower than that for the first two values.

Also listed in Table 7-2 are the operating conditions for these tests. The spray dryer inlet temperature averaged 329°F. The approach to adiabatic saturation averaged 20°F, as measured at the fabric outlet. Actually, due to heat losses in the system and incidental air in-leakage, the adiabatic saturation temperature at the fabric filter outlet is approximately 2°F lower than at the spray dryer inlet. Thus, the approach to adiabatic saturation based on the spray dryer inlet adiabatic saturation temperature was approximately 18°F. The flue gas flow rate averaged 429,000 acfm, based on spray dryer inlet conditions. This represents approximately 86 percent of the design flue gas flow rate for the system, which was reported to be 500,000 acfm. The daytime boiler load was held at 65 MW through most of this week of tests. The solids content in the atomizer feed slurry averaged 29 weight percent. At this solids content, inlet temperature, sulfur level, and reagent ratio, the resulting recycle ratio averaged 12.5:1. This value is calculated by the following equation:

$$\text{Recycle Ratio} = \frac{\text{Recycle material added to mix tank, lb}}{\text{Lime (CaOH}_2\text{) solids in lime slurry added, lb}} \qquad (7\text{-}2)$$

The value in Table 7-2 was calculated based on the lime addition rate as quantified by the lime slurry flow rate and solids content. The recycle ratio based on the weigh belt readings and on the atomizer feed solids analysis averaged 13.6:1 and 11.8:1, respectively.

An additional entry in Table 7-2 is the relative accuracy of energy balance calculations for these data points. The energy balance compares the sensible and latent heat required to raise the water in the atomizer feed slurry to the adiabatic saturation temperature, evaporate it, and raise the vapor to the spray dryer outlet temperature, to the sensible heat required to lower the inlet flue gas to the spray dryer outlet gas temperature. The net energy balance is the amount of thermal energy required to heat and evaporate the water in the atomizer feed slurry minus that required to cool the inlet flue gas. Other terms in this balance include the effects of a small flow of atomizer wheel protection water, moisture remaining in the spray-dried solids, kinetic and potential energies for the slurry and flue gas streams, and enthalpies of reactions within the spray dryer. These terms tend to be rather small in magnitude and tend to offset one another. Consequently, these terms have been ignored in these balances. The relative accuracy is defined as this net energy balance divided by the amount of thermal energy required to heat and evaporate the water in the atomizer feed slurry.

The amount of thermal energy required to heat and evaporate the water in the atomizer feed slurry is calculated from the atomizer feed slurry flow rate, weight percent solids, and specific gravity, and the slurry temperature, adiabatic saturation temperature, and spray dryer outlet temperature. The slurry flow rate measurement is the major factor in determining the accuracy of this term. The energy required to cool the flue gas is based on the inlet flue gas flow rate and specific heat. The flue gas flow rate is calculated from a linear-least-squares fit correlation of inlet flue gas flow rate as measured by velocity traverse of the inlet duct cross-section to the square root of the roof gas disperser pressure drop.

Thus, these energy balances provide a check of the atomizer feed slurry flow rate measurement relative to the flue gas flow rate measurement.

A relative accuracy value of 0.0 indicates either perfect measurements, or exactly off-setting errors. A positive value indicates that either the atomizer feed slurry flow rate measurement is too high or the flue gas flow rate measurement is too low. Conversely, a negative value indicates that the actual atomizer feed slurry flow rate is lower than indicated or that the actual flue gas flow rate is higher than that indicated. Considering that these measurements are being made on a full-scale installation, a relative accuracy of ±5 percent would be considered excellent agreement. A value between ±5 percent and ±10 percent is still quite acceptable.

The value of -0.9 percent for the average relative accuracy for these tests, with a standard deviation of 2.5 percent, shows excellent agreement between slurry and flue gas flow rate measurements. Combined with the good agreement seen in the three methods of calculating reagent ratio requirements, these energy balance data inspire a great deal of confidence in the accuracy of the measurements made in these tests.

Finally, a mean spray dryer vessel residence time for the 40 hours of data is presented. This value is calculated from the flue gas flow rate at spray dryer outlet conditions and the spray dryer vessel volume. The spray dryer volume was calculated from nominal dimensions to be 81,900 ft^3. Because of the lack of precision in calculating vessel volume introduced by using nominal measurements, vessel residence time is reported only to the nearest second. Also, no standard deviation is reported.

Table 7-4 summarizes the results of 75 percent SO_2 removal set point, nominal 2.3:1 air-to-cloth ratio tests for the low sulfur coal conditions. The results show that the set point SO_2 removal was very nearly the exact average for this test period. The reagent ratio requirements averaged somewhat lower for these tests than for the nominal 2:1 air-to-cloth ratio tests at the same SO_2 removal set point. However, considering that the nominal 2:1 air-to-cloth ratio tests had fewer than half the number of data points and considering that the difference in the two averages is less than 0.1, the difference may not be significant. To put this difference into perspective, it should be noted that the difference between the two values is less than the standard deviation for either value. The other methods of evaluating reagent ratio, based on the quicklime weight belt readings and the atomizer feed slurry flow rate and analyses, averaged 0.54 and 0.65,

TABLE 7-4. TEST RESULTS FOR THE 75% SO_2 REMOVAL SET POINT, NOMINAL 2.3:1 AIR-TO-CLOTH RATIO TESTS FOR LOW SULFUR COAL CONDITIONS

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	74.8	3.3	80
Spray Dryer Removal (percent)	66.5	3.9	86
Fabric Filter Removal (percent)	8.3	2.7	80
Reagent Ratio	0.62[a]	0.12	86
Test Conditions			
Spray Dryer Inlet Temperature (°F)	338	11.6	89
Approach to Adiabatic Saturation (°F)	20[b]	1.0	89
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	446×10^3		
Percent of Design Flue Gas Flow Rate	89	14	89
Solids in Atomizer Feed Slurry (weight percent)	30	2	89
Recycle Ratio	14.5:1[c]	3.0:1	89
Relative Accuracy of Energy Balances (percent)	-1.9	2.9	89
Flue Gas Residence Time in Spray Dryer Vessel (sec)	13	-	89
Fabric Filter Air-To-Cloth Ratio	1.8:1[d,e]	0.3:1	81

[a] Based on lime slurry solids content and feed rate

[b] Based on adiabatic saturation temperature measured at the fabric filter outlet

[c] Based on ratio of recycle material introduced at mix tank to lime solids (dry basis) in lime slurry makeup to mix tank

[d] Actual arithmetic mean calculated for hours averaged, differs from desired nominal value

[e] Gross ratio, ignores effects of taking compartments off-line for cleaning and ignores reverse gas flow

respectively. These alternate calculation approaches tend to support the observation that a slightly lower reagent ratio value was required in the nominal 2.3:1 air-to-cloth ratio tests. However, even if this observed slightly lower value is accurate, it is not clear that this effect is solely a result of operating the fabric filter at a slightly higher air-to-cloth ratio. Other minor effects that were not documented, such as potential variations in coal ash alkalinity, could have effected this small observed change in reagent ratio.

The operating conditions showed an average spray dryer inlet temperature of 338°F and an average approach temperature of 20°F (based on the adiabatic saturation temperature measured at the fabric filter outlet). The flue gas flow rate averaged 446,000 acfm, or approximately 90 percent of the design flow rate. As listed later in the table, this flue gas flow rate resulted in an average spray dryer vessel residence time of approximately 13 seconds. The daytime boiler load for these tests varied from 60 to 80 MW. This test period included one Saturday of operation and one overnight period at 80 MW due to NSP system electric demand. The weight percent solids for the atomizer feed averaged just over 30 percent, resulting in a relatively large recycle ratio of 14.5:1. Also, the average relative accuracy for the energy balances for these data indicate good agreement between flow rate measurements. The results in Table 7-4 also show the split between the spray dryer contribution and the fabric filter contribution to overall SO_2 removal. The spray dryer removal contribution was calculated by the following equation:

$$\begin{array}{l}\text{Spray Dryer}\\ SO_2 \text{ Removal}\end{array} = \frac{(SO_2 \text{ in SD inlet, lb-mole}) - (SO_2 \text{ in SD outlet, lb-mole})}{SO_2 \text{ in SD inlet, lb-mole}} \times 100 \qquad (7\text{-}3)$$

The fabric filter SO_2 removal was calculated as its contribution to overall system SO_2 removal. By defining fabric filter SO_2 removal in this way, the individual contributions of the spray dryer and fabric filter can be directly summed to result in the overall removal. The fabric filter contribution was calculated by the following equation:

$$\text{Fabric Filter } SO_2 \text{ Removal} = \frac{(SO_2 \text{ in SD outlet, lb-mole}) - (SO_2 \text{ in FF outlet, lb-mole})}{SO_2 \text{ in SD inlet, lb-mole}} x100 \qquad (7\text{-}4)$$

The results show that the fabric filter contribution to overall removal was relatively small, about 8 percent out of 75 percent overall. Although not shown in the table, the SO_2 removal across the fabric filter based on the fabric filter inlet SO_2 concentration can also be easily calculated. In this case, the SO_2 remaining in the spray dryer outlet (fabric filter inlet) is 33.5 percent of the SO_2 in the system inlet. Thus, the SO_2 removal across the fabric filter based on the actual fabric filter inlet SO_2 content can be calculated as:

$$\frac{8.3}{33.5} \text{ x } 100 = 25 \text{ percent} \qquad (7\text{-}5)$$

This percent removal seems relatively low. However, since the desired 75 percent SO_2 removal level was achieved with sub-stoichiometric amounts of lime, it is apparent that there was little excess lime available for removal reactions in the fabric filter.

Similar data were not presented in Table 7-2 for the 75 percent SO_2 removal set point, nominal 2:1 air-to-cloth ratio tests. Problems with the response time of the 150-ft spray dryer outlet sample line on the CEMS had not yet been resolved during that first week of meaningful test work.

Consequently, valid spray dryer outlet SO_2 and O_2 concentration values were not available for that week of testing for use in Equations 7-3 and 7-4 to calculate individual component SO_2 removal contributions.

A final entry in Table 7-4 is the calculated, average air-to-cloth ratio for this test period. Note that the average of 1.8:1 is below the desired air-to-cloth ratio of 2.3:1. In fact, the average plus one standard deviation is below the desired value. There are two apparent reasons for this average being low. First, the flue gas flow rates measured during the low sulfur coal portion of this program were approximately 10 percent lower than correlations developed by Joy/Niro predicted. Since the number of compartments on-line was set by this previous flow rate correlation, the air-to-cloth ratio calculated with these current data would be expected to fall approximately 10 percent lower than desired. Second, the number of compartments on-line was adjusted each day to correspond to the maximum boiler load, which was usually achieved at mid-morning. As unit load decreased in the late afternoon, the number of compartments on-line was generally not reduced. This often resulted in operating the unit a number of hours each day at air-to-cloth ratios well below the desired value.

No values for air-to-cloth ratio were presented in Table 7-2 for the 75 percent SO_2 removal set point, nominal 2:1 air-to-cloth ratio low sulfur coal test period. Because this test period was conducted during the first productive week of the test program, data recording routines were not yet well established. Consequently, accurate data on the number of compartments on-line for this week of operation were not recorded.

A final note should be made about the fabric filter air-to-cloth ratio calculations. The calculations are based on the number of compartments on-line and a calculated cloth area of 26,775 ft^2 per compartment, excluding seams, bands, and cuffs. The effects of taking each compartment off-line once-per-hour and the corresponding momentary reverse gas flow have been ignored. With 8 compartments on-line only 12 minutes per hour involve a compartment being off-line for cleaning, and an even smaller fraction of time with reverse gas flow.

Table 7-5 summarizes the results of the last of the low sulfur coal tests, with a 90 percent SO_2 removal set point and a nominal 2:1 air-to-cloth ratio at the fabric filter. The results show that the average SO_2 removal was less than one percent below the 90 percent set point. The reagent ratio requirement averaged 0.82, still sub-stoichiometric in spite of the higher SO_2 removal requirement. The fabric filter contribution to overall SO_2 removal was increased to between 10 and 11 percent out of the 89 percent overall average, up from about 8 percent in the 75 percent overall tests. The fabric filter SO_2 removal as a percentage of the SO_2 content in the fabric filter inlet flue gas was increased to 50 percent during this test period.

The three approaches to calculating reagent ratio showed excellent agreement for these tests. The reagent ratios calculated on the basis of weigh belt readings and on the basis of atomizer feed rate and solids analyses averaged 0.82 and 0.81. The values are essentially identical to that in Table 7-5.

The operating conditions in Table 7-5 show an average inlet temperature of 340°F and an approach to adiabatic saturation of 20.5°F (based on adiabatic saturation measured at the fabric filter outlet). These values are similar to those for the previous 75 percent SO_2 removal low sulfur coal tests. The average spray dryer inlet flue gas rate was 493,000 acfm, or just below the design rate of 500,000 acfm. This flow rate corresponds to a spray dryer vessel residence time of 12 seconds. The daytime boiler load varied from 60 to 85 MW during these tests. The solids in the atomizer feed slurry averaged 29 percent, similar to the average for the 75 percent SO_2 removal tests. Because a higher reagent ratio was required to achieve 90 percent rather than 75 percent SO_2 removal, the recycle ratio was reduced to between 10:1 and 12:1 rather than 12:1 to 14:1 for the previous tests. As

TABLE 7-5. TEST RESULTS FOR THE 90% SO_2 REMOVAL SET POINT, NOMINAL 2:1 AIR-TO-CLOTH RATIO TESTS FOR LOW SULFUR COAL CONDITIONS

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	89.2	4.6	75
Spray Dryer Removal (percent)	78.5	5.9	78
Fabric Filter Removal (percent)	10.7	2.8	75
Reagent Ratio	0.82[a]	0.21	78
Test Conditions			
Spray Dryer Inlet Temperature (°F)	340	15	78
Approach to Adiabatic Saturation (°F)	20.5[b]	1.3	78
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	493×10^3	72×10^3	78
Percent of Design Flue Gas Flow Rate	99	14	78
Solids in Atomizer Feed Slurry (weight percent)	29	2	78
Recycle Ratio	10.7:1[c]	3.7:1	78
Relative Accuracy of Energy Balance Calculations (percent)	0.8	2.7	78
Flue Gas Residence Time in Spray Dryer Vessel (seconds)	12	-	78
Fabric Filter Air-to-Cloth Ratio	1.6:1[d,e]	0.2:1	75

[a] Based on lime slurry solids content and feed rate

[b] Based on adiabatic saturation temperature measured at the fabric filter outlet

[c] Based on ratio of recycle material introduced at mix tank to lime solids (dry basis) in lime slurry makeup to mix tank

[d] Actual arithmetic mean calculated for hours averaged, differs from desired nominal value

[e] Gross ratio, ignores effects of taking compartments off-line for cleaning and ignores reverse gas flow

for the previous tests, the relative accuracy average for the hourly energy balances was a suitably low value, 0.8 percent for these tests.

The air-to-cloth ratio for this test period averaged 1.6:1. As expected based on the previous discussions of how the number of compartments on-line was set, the air-to-cloth ratio for this test period was about 12 percent lower than that during the higher air-to-cloth ratio test period summarized in Table 7-4. However due to the considerations also discussed previously, the actual air-to-cloth ratio for this test period averaged well below the desired value of 2:1.

Figure 7-1 is a trend plot which illustrates one week of system operation during the 90 percent SO_2 removal, nominal 2:1 air-to-cloth ratio low sulfur coal test period. Plotted are (from the bottom) reagent ratio, recycle ratio, approach temperature, flue gas flow rate (percent of design gas flow) and overall system SO_2 removal. The reagent ratio and recycle ratio values depicted are based on lime and recycle weigh belt measurements. These values are plotted because they are most indicative of control system responses to changes in unit operating conditions. The time plotted is the week from Monday, August 15th, through Friday, August 19th. The plots depict unit startup on Monday morning, shut down on Friday evening, several upsets during the week, and periods of normal operation at both full and reduced loads. This week was chosen for illustration because it includes approximately one-half of the data used in the averages in Table 7-5, and because it includes many of the types of upsets that were encountered during the low sulfur coal test period.

Starting Monday morning, the flue gas flow rate shows a minor "blip" between 0100 and 0200 (1 and 2 a.m.) where the boilers were banked. That is, they were briefly fired to restore steam header pressure. Then, at approximately 0400 (4 a.m.), the startup of the unit began. Full flue gas flow was established for about 4 hours at 110 percent of the design rate, then at 1100 (11 a.m.), the spray dryer rotary atomizer tripped. The approach to adiabatic saturation had been lowered as far as an average of 26°F for 1000

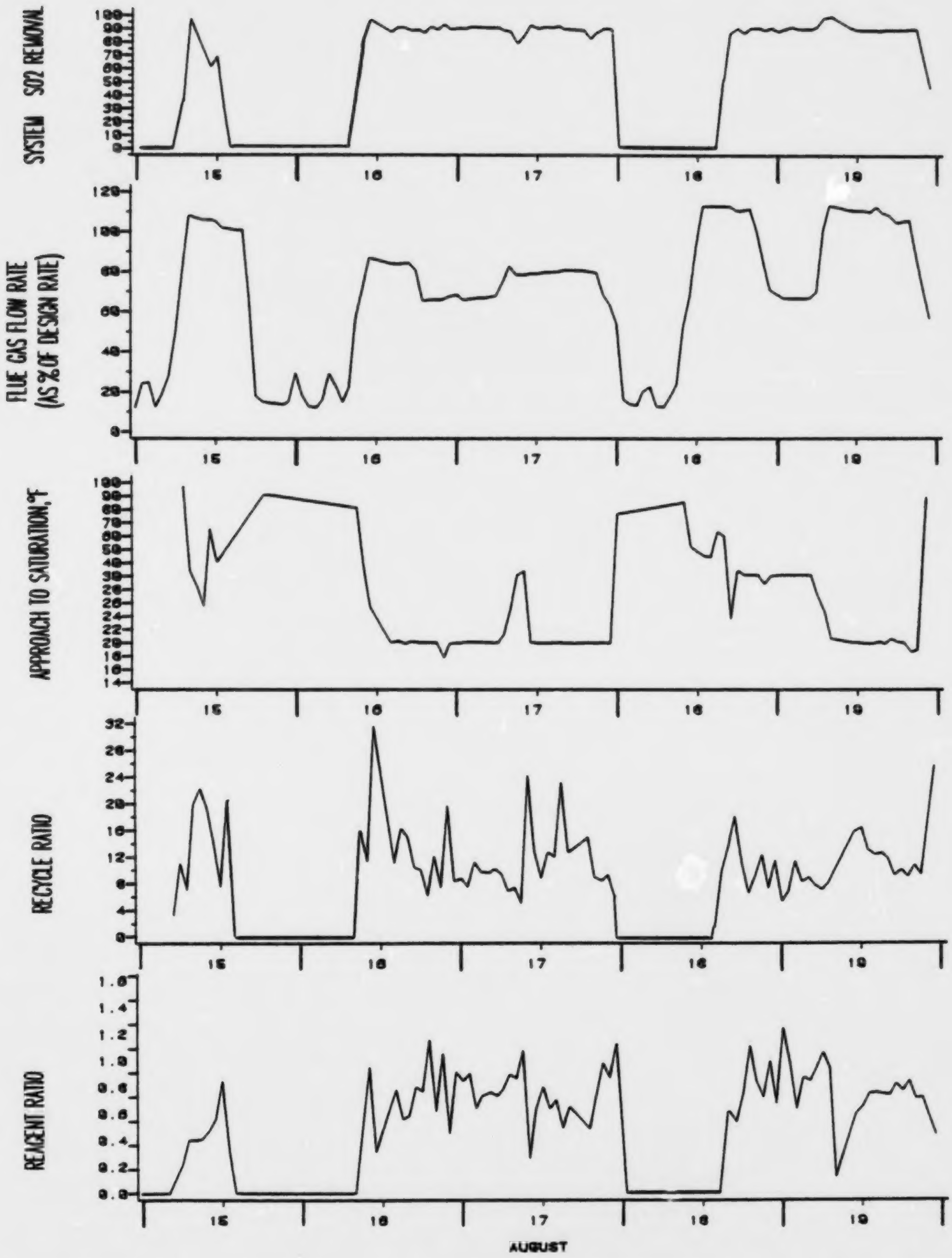

Figure 7-1. Trend plot of major system parameters during one week of low sulfur coal operation.

(10 a.m.) (indicating the transition from a 30°F approach to a 20°F approach during that hour), but was quickly raised as the atomizer feed was interrupted. This atomizer trip was one where the atomizer feed was not shut off before the atomizer shut down. As described in Section 6, this error caused slurry to overflow the standing wheel, flow up the spindle to which the wheel is attached, and contaminate the lubricating oil in the lower oil sump. Although the atomizer was initially started up after the trip, it was consequently shut down at 1300 (1 p.m.), after slurry was discovered in the oil sump. The unit was off-line by 1800 (6 p.m.). During the brief period of operation before the atomizer trip that morning, the unit never achieved steady operating conditions with respect to approach to saturation or SO_2 removal.

The atomizer was cleaned and put back in service that evening, and at 0800 (8 a.m.) the following morning, startup began once more. The startup, on the morning of Tuesday, August 16th, was more typical or "normal." By the time full boiler load was established at 1100 (11 a.m.), the approach to saturation was lowered from 30°F to 20°F (based on the wet bulb at the fabric filter outlet). After an initial overshoot and undershoot, the average SO_2 removal across the system was near the set point of 90 percent and relatively steady by 1500 (3 p.m.).

The system ran relatively smoothly until approximately 0600 (6 a.m.) the next morning on Wednesday, August 17th. However, a reduction in load at approximately 1700 (5 p.m.) briefly upset SO_2 removal control. At approximately 0800 (8 a.m.) on the 17th, shortly after the unit load was restored, the flow of atomizer feed slurry was temporarily interrupted when the atomizer feed pumps were changed and the suction line on the pump going into service was found to be plugged. This upset caused the approach temperature to average near 30°F for two hours and caused the system SO_2 removal to fall below the set point for three hours.

The system again ran smoothly until 2300 (11 p.m.) on the 17th, when the rotary valve at the bottom of the recycle storage bin failed. The unit was shut down at midnight, pending repair of the plugged recycle rotary valve. Actually, this upset did not require that the unit be shut down for repairs. The spray dryer system could have easily been operated in the once-through mode, at a 30 to 40°F approach to saturation until the flow of recycle material could be restored. However, since the electric power generated by this peaking unit is not needed by the NSP system in the late night and early morning hours, it was thought to be more economical to shut down for several hours rather than run in the less lime-efficient once-through mode.

System startup was begun at approximately 0930 (9:30 a.m.) the next morning, on Thursday, August 18th. This was an almost normal startup as the SO_2 removal quickly reached the setpoint value, went through a normal overshoot and undershoot about the setpoint, then stabilized near the setpoint value. However, the approach temperature was held at elevated values and the system was operated in the once-through mode for several hours after startup because the rotary valve was still not repaired. The startup was called for by the NSP system power requirements in spite of the rotary valve not being repaired. The FGD system easily achieved 90 percent SO_2 removal in spite of the once-through operation. The rotary valve was repaired on the afternoon of the 18th, the flow of recycle material was restored, and the approach temperature was lowered to 20°F at approximately 1800 (6 p.m.)

Less than 1 hour after the approach was lowered to 20°F, one of the two continuous wet bulb monitors in operation at the fabric filter outlet ran dry. Since the system control logic requires that two of potentially three continuous wet bulb monitors be in service in order to run in the approach temperature control mode, the control system reverted to a constant spray dryer outlet temperature control mode. The constant outlet temperature set point corresponds to approximately a 30°F approach to saturation. Although the wet bulb monitor was quickly refilled with water and put back in service, the FGD system control operator neglected to put the system back in the approach temperature control mode. Consequently, the system ran at approximately a 30°F approach to saturation from 1830 (6:30 p.m.) to 0730 (7:30 a.m.) the next morning.

When the approach temperature was lowered from 30°F to 20°F, system overall SO_2 removal was raised to 100 percent for two hours. This was caused by several aspects of the atomizer feed system design. The lime content of the atomizer feed slurry, and hence the reagent ratio had been raised by the control system to compensate for the 30°F approach temperature in order to maintain 90 percent overall SO_2 removal levels. When the approach temperature was lowered to 20°F, the atomizer feed slurry rate was slightly increased because of the 10°F increase in spray down temperature across the spray dryer. This led to a temporary further increase in reagent ratio. However, because the approach temperature was lowered, the reagent ratio requirements to achieve 90 percent setpoint were actually reduced. Consequently, system SO_2 removal temporarily increased to 100 percent, well above the 90 percent setpoint. Even though the process control system lowered the lime feed rate dramatically as soon as the approach temperature was lowered (as seen by the very low lime weigh belt reagent ratio values in the plot), the long slurry residence times in the mix tank and atomizer feed tank led to nearly 100 percent SO_2 removal for 2 hours before the reagent ratio at the atomizer feed could be lowered to achieve just 90 percent overall SO_2 removal.

Once the system approach temperature and overall removal was restored, the system ran smoothly until the normal shut down at 2300 (11 p.m.) on Friday, August 19th.

During this one week of operation, 42 hours of the total of 78 hours in Table 7-5 were achieved. Had the system operated with no upsets, approximately 60 hours of normal full load operation would have been encountered (12 hr/day x 5 days). Although numerous upsets occurred during this week, most occurred when the unit was (or would have been) at reduced load. This is in part fortuitous, but it also supports the contention presented in Section 6 that many problems encountered during this program were related to the relative inexperience of the FGD system operators at running the conditions required by this test program. The best example of this effect was the Thursday evening upset where the control operator failed to restore approach temperature control after a wet bulb monitor went dry. Since the unit had previously normally operated at constant spray dryer outlet temperature rather than with approach temperature control, this oversight is perfectly understandable. The oversight went uncorrected for a number of hours because no one associated with this test program was on site during off-shift hours. However, because the unit was at low load as well during this time period, few if any full load test hours were lost by this upset.

The amount of downtime related to some process upsets (e.g., the incident of slurry in the lower atomizer lube oil sump and the failed recycle bin rotary valve) cannot be considered representative of what might be encountered on other systems. Because this is a peaking unit, the utility had little reason to correct a problem which occurred in the afternoon any sooner than by the following morning.

Of the numerous problems encountered during this week, none appear to indicate any limitations on the technology. For example, incidences of slurry entering the lower atomizer lubricating oil sump while feeding slurry to a non-rotating wheel can be largely eliminated through the use of a properly implemented interlock system and through increased operator awareness of the potential problem. Problems with slurry pump suction lines plugging can be reduced by applying many of the fixes learned from wet scrubbing experience. Incidences of operator oversight will in general be reduced in frequency as the system operators gain experience with the system.

Figure 7-2 illustrates the hours of operation during this week which contributed to the average performance values in Table 7-5. A comparison of Figures 7-1 and 7-2 provides an explanation of the degree of editing of data which preceded the establishment of average system performance in Table 7-2 and Tables 7-3 through 7-5.

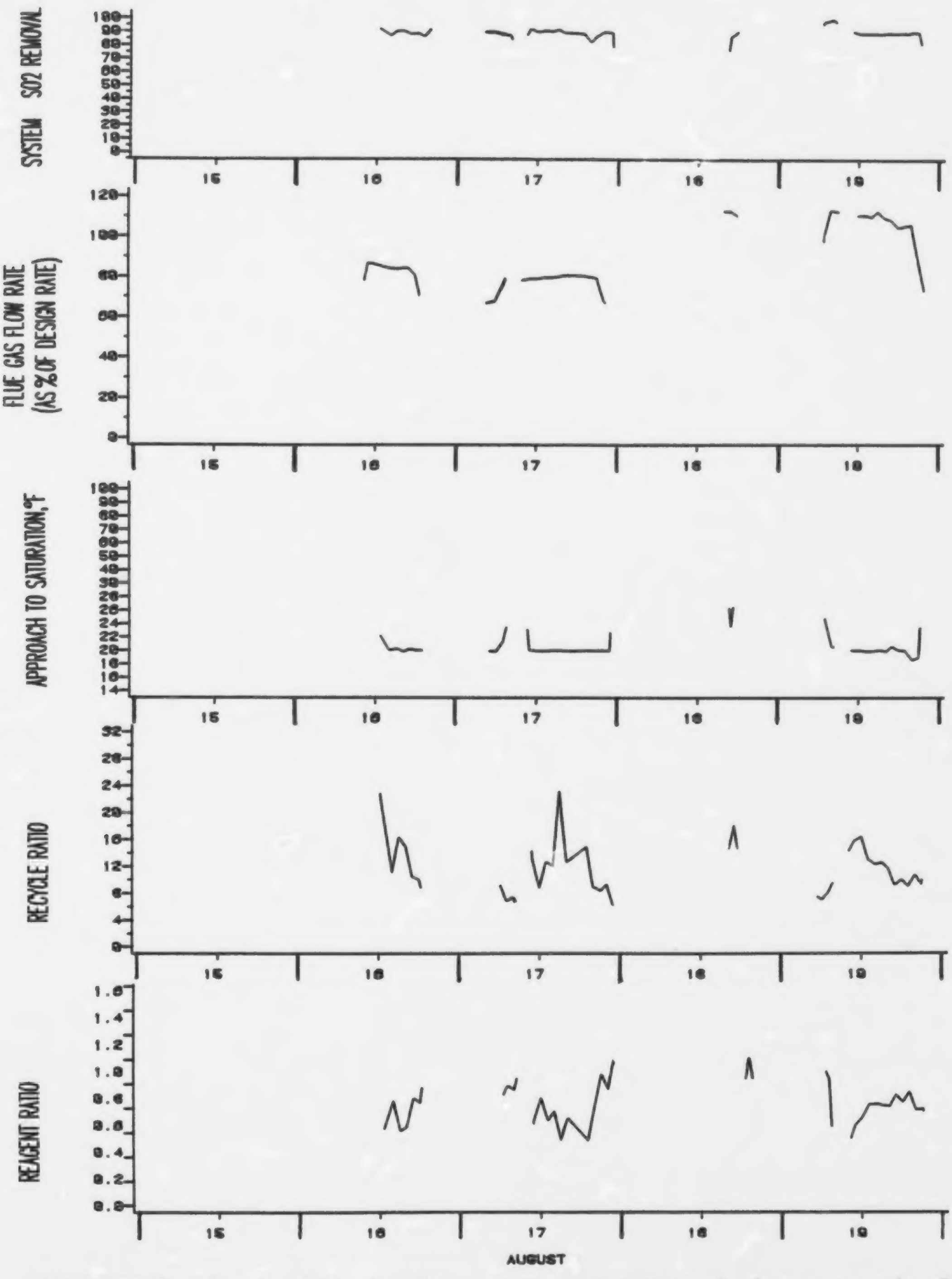

Figure 7-2. Trend plot of major system parameters during one week of low sulfur coal operation, edited to show only data used in test averages.

The three low sulfur coal test periods each included time periods when the unit load was reduced to 50 MW or lower. These time periods were primarily overnight on Monday through Thursday of each week. Data were recorded and reduced for these periods and are summarized in Tables 7-6 through 7-8. The reagent ratio values are of questionable accuracy for these time periods, because no lime slurry or atomizer feed samples were taken during these off hours. The results show that slightly higher reagent ratios were required to achieve the average SO_2 removals, although this apparent increase may be entirely the result of experimental errors due to the lack of manual measurements during these periods. However, slightly higher reagent ratios at lower loads are consistent with other impacts of low load: lower dryer inlet temperatures, correspondingly lower spray down temperatures (both reduced by about 20°F), and subsequently lower recycle ratios.

Flue gas flow rates were reduced to around 330,000 acfm, or about 66 percent of design flow rate. These flue gas flow rates correspond to a spray dryer vessel residence time of approximately 18 seconds. Because fabric filter compartments were not brought off line during these low load periods the air-to-cloth ratios for these periods averaged between 1.1:1 and 1.3:1.

7.1.2 High Sulfur SO_2 Removal Results

The high sulfur coal burned was an Illinois No. 6 from the Peabody Coal Company. Table 7-9 summarizes analyses of three spot samples randomly collected during the high sulfur coal test period. The heating values of the three spot samples of the coal ranged from 10,620 Btu/lb to 10,792 Btu/lb on an as-received basis. The sulfur content of these three samples varied from 2.95 to 3.37 percent. Current New Source Performance Standards for utility boilers would require 90 percent SO_2 removal when this coal is burned. When burned in the Riverside boilers, the coal produced a flue gas with an SO_2 concentration of approximately 1900 to 2100 ppm, at oxygen contents of 7 to 8 percent. The alkaline species in the coal ash ($CaO + MgO + Na_2O + K_2O$) represented less than 10 percent of the ash on a weight basis.

TABLE 7-6. TEST RESULTS FOR THE 75% SO_2 REMOVAL SET POINT, 2:1 AIR-TO-CLOTH RATIO FOR LOW SULFUR COAL CONDITIONS (LOW BOILER LOAD)

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	72.3	5.7	33
Reagent Ratio	0.82[a]	0.21	33
Test Conditions			
Spray Dryer Inlet Temperature (°F)	318	8	33
Approach to Adiabatic Saturation (°F)	20[b]	0.5	33
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	336×10^3	8×10^3	33
Percent of Design Flue Gas Flow Rate	67	2	33
Solids in Atomizer Feed Slurry (weight percent)	29	1.3	33
Recycle Ratio	11.4:1[a]	3.9:1	33
Relative Accuracy of Energy Balance Calculations (percent)	-2.9	1.9	33
Flue Gas Residence Time in Spray Dryer Vessel (seconds)	18	-	33

[a] Based on instrument readings, not supported by manual measurements

[b] Based on the adiabatic saturation temperature measured at the fabric filter outlet

TABLE 7-7. TEST RESULTS FOR THE 75% SO_2 REMOVAL SET POINT, 2.3:1 AIR-TO CLOTH RATIO FOR LOW SULFUR COAL CONDITIONS (LOW BOILER LOAD)

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	76.3	3.6	22
Spray Dryer Removal (percent)	69.8	3.7	22
Fabric Filter Removal (percent)	6.6	1.3	22
Reagent Ratio	0.72[a]	0.15	22
Test Conditions			
Spray Dryer Inlet Temperature (°F)	318	5	22
Approach to Adiabatic Saturation (°F)	20[b]	0.3	22
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	326×10^3	19×10^3	22
Percent of Design Flue Gas Flow Rate	65	4	22
Solids in Atomizer Feed Slurry (weight percent)	30	1.2	22
Recycle Ratio	13.0:1[a]	3.7:1	22
Relative Accuracy of Energy Balance Calculations (percent)	-5.3	3.3	22
Flue Gas Residence Time in Spray Dryer Vessel (seconds)	18	-	22
Fabric Filter Air-to-Cloth Ratio	1.3:1[c,d]	0.1:1	22

[a] Based on instrument readings, not supported by manual measurements

[b] Based on the adiabatic saturation temperature measured at the fabric filter outlet

[c] Actual arithmetic mean calculated for hours averaged, differs from desired nominal value

[d] Gross ratio, ignores effects of taking compartments off-line for cleaning and ignores reverse gas flow

TABLE 7-8. TEST RESULTS FOR THE 90% SO_2 REMOVAL SET POINT, 2:1 AIR-TO-CLOTH RATIO FOR LOW SULFUR COAL CONDITIONS (LOW BOILER LOAD)

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	89.5	3.4	21
Spray Dryer Removal (percent)	82.1	1.9	21
Fabric Filter Removal (percent)	7.4	2.3	21
Reagent Ratio	0.96[a]	0.21	21
Test Conditions			
Spray Dryer Inlet Temperature (°F)	310	4	21
Approach to Adiabatic Saturation (°F)	20[b]	0.5	21
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	335×10^3	8×10^3	21
Percent of Design Flue Gas Flow Rate	67	2	21
Solids in Atomizer Feed Slurry (weight percent)	29	2	21
Recycle Ratio	8.3:1[a]	2.5:1	21
Relative Accuracy of Energy Balance Calculations (percent)	0.0	2.0	21
Flue Gas Residence Time in Spray Dryer Vessel (seconds)	18	-	21
Fabric Filter Air-to-Cloth Ratio	1.1:1[c,d]	0.1:1	21

[a] Based on instrument readings, not supported by manual measurements

[b] Based on the adiabatic saturation temperature measured at the fabric filter outlet

[c] Actual arithmetic mean calculated for hours averaged, differs from desired nominal value

[d] Gross ratio, ignores effects of taking compartments off-line for cleaning and ignores reverse gas flow

TABLE 7-9. SUMMARY OF HIGH SULFUR COAL ANALYSES

Ultimate Analysis (wt %)[a]	Sample 1	Sample 2	Sample 3
Moisture	13.12	14.52	13.73
Carbon	59.46	58.39	59.69
Hydrogen	4.29	4.15	4.29
Nitrogen	0.94	0.93	0.99
Sulfur	2.95	3.37	3.12
Ash	11.46	10.83	10.28
Oxygen[b]	7.78	7.81	7.90
Higher Heating Value (Btu/lb)[a]	10719	10620	10792
Elemental Analysis of Ash (wt %)			
SiO_2	49.36	47.25	48.91
Al_2O_3	18.16	17.69	18.05
TiO_2	0.64	0.66	0.74
Fe_2O_3	15.72	16.35	15.82
CaO	6.27	6.17	5.40
MgO	0.95	0.99	1.02
Na_2O	0.76	0.75	0.71
K_2O	1.87	1.75	1.87
P_2O_5	0.26	0.17	0.17
SO_3	5.93	6.75	5.32
TOTAL	99.92	98.53	98.01

[a] As received basis

[b] By difference

As discussed earlier, the Riverside FGD system was not really designed to treat flue gas from high sulfur coal on a continuous basis. In earlier testing the lime requirements for high sulfur coal operation were supplied by operating the ball mill and attrition slakers simultaneously. The lime slaking rate capacity of the attrition slaker which was used alone during these high sulfur tests was somewhat limited by the sizing of the slaking water supply piping. Because the amount of water that could be fed to the lime slaker was limited, the maximum lime slaking rate was not much greater than the steady state lime requirement. Thus, the system had difficulty in returning to the requisite 90 percent removal efficiency following any perturbation which reduced system SO_2 removal. The system was generally not able to quickly return to set point SO_2 removal by briefly adding lime at a high rate, because of the lime slaking rate limitation. Instead, system SO_2 removal tended to asymptotically approach the set point value of 90 percent over several hours.

Baseline High Sulfur Coal Tests

Table 7-10 summarizes the SO_2 removal results for the baseline high sulfur coal, 90 percent SO_2 removal set point tests. The fabric filter air-to-cloth ratio for these tests was maintained at a nominal value of 2:1. The results show that the average SO_2 removal was nearly 2 percent below the 90 percent set point. This was expected due to the lime slaking rate limitations mentioned above. The reagent ratio required to achieve nearly 90 percent SO_2 removal across the system averaged 1.33. The reagent ratio based on the quicklime weigh belt readings averaged 1.17. However, comparison of quicklime weigh belt readings integrated with respect to time to the number of truckload shipments of lime over a period of one week indicated that the weigh belt readings were on the average approximately 10 percent low. This gross calibration was completed during the high sulfur coal tests and takes into account 15 truck-loads of lime. This calibration also considered the beginning and ending quicklime silo levels, so it is considered to be relatively accurate. Increasing the reagent ratio calculated from weigh belt readings, to correct for this apparent bias, raises this value to

TABLE 7-10. TEST RESULTS FOR THE HIGH SULFUR COAL, 90% REMOVAL SET POINT, 2:1 AIR-TO-CLOTH RATIO TESTS

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	88.1	3.0	174
Spray Dryer Removal (percent)[a]	72.8	1.9	11
Fabric Filter Removal (percent)[a]	16.2	1.2	11
Reagent Ratio	1.33	0.12	174
Test Conditions			
Spray Dryer Inlet Temperature (°F)	322	6	176
Approach to Adiabatic Saturation (°F)	20[b]	0.9	176
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	412×10^3	18×10^3	176
Percent of Design Flue Gas Flow Rate	82	4	176
Solids in Atomizer Feed Slurry (weight percent)	30	2	176
Recycle Ratio	2.0:1[c]	0.4:1	175
Relative Accuracy of Energy Balance Calculations (percent)	-6.7	2.8	175
Flue Gas Residence Time in Spray Dryer Vessel (seconds)	14	-	176
Fabric Filter Air-to-Cloth Ratio	2.0:1[d,e]	0.2:1	174

[a] Due to oxygen analyzer response time problems, accurate oxygen values for the spray dryer outlet flue gas sample were not available. The limited number of data presented were collected after this response problem was corrected. Because few data are included in this average, the totals do not exactly agree with the overall SO_2 removal value presented above

[b] Based on the adiabatic saturation temperature measured at the fabric filter outlet

TABLE 7-10 (Continued)

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[c] Based on ratio of recycle material introduced at mix tank to lime solids (dry basis) in lime slurry makeup to mix tank

[d] Actual arithmetic mean calculated for hours averaged differs from desired nominal value

[e] Gross ratio, ignores effects of taking compartments off-line for cleaning and ignores reverse gas flow

1.3 as well. Finally, the reagent ratio based on lime makeup rates calculated from the atomizer feed rate and solids analysis agreed almost exactly with the value in Table 7-10, averaging 1.35. This approach is most accurate for higher sulfur conditions, or other conditions resulting in relatively low recycle ratios, as the atomizer feed solids contain more nearly equal quantities of lime and recycle material.

The reagent ratio of approximately 1.3 is considerably higher than that required for 90 percent removal conditions in the low sulfur coal tests. The higher sulfur levels, somewhat lower spray down temperatures, lower recycle ratios, and much less alkaline ash each perhaps contributed to increased reagent ratio requirements in the high sulfur coal tests. Also, the fabric filter contribution to overall SO_2 removal was found to be more significant in this test, increasing to 16 percent out of 88 percent overall from 11 percent out of 89 percent overall SO_2 removal in the low sulfur test. Based on the quantity of SO_2 in the flue gas at the fabric filter inlet, this removal level corresponds to a 60 percent SO_2 removal across the fabric filter.

The spray dryer inlet temperature averaged 322°F for these tests, or approximately 15 to 20°F lower than that during the low sulfur tests. The spray down temperature for the high sulfur tests was reduced by a similar amount, as the adiabatic saturation temperature was not greatly different. The flue gas flow rate averaged 412,000 acfm, or 82 percent of design. The boiler load was generally maintained at 65 to 67 MW during these tests. Higher loads were not run because of the lime slaking rate limitations.

The weight percent solids in the atomizer feed slurry averaged 30 percent for these tests, similar to that for the low sulfur tests. However, the effects of a higher sulfur content, higher reagent ratio requirements, and a slightly reduced spray down temperature combined to reduce the recycle ratio to an average of 2.0:1. In contrast, the 90 percent SO_2 removal low sulfur coal tests saw an average recycle ratio of nearly 11:1. The relative accuracy for the energy balances for this test period was not as close as for the low sulfur tests; however, the average value of -6.6 percent still shows acceptable agreement between the atomizer feed slurry and flue gas flow rate measurements.

Throughout most of the high sulfur coal tests, the unit load was maintained at 65 to 67 MW around the clock from Monday to Friday. The firing characteristics of the high sulfur coal were such that the unit load could not be reduced much below 60 MW without taking one boiler off line. This approach has a negative impact on the spray dryer control system, as the inlet flue gas is badly stratified with respect to temperature and SO_2 concentration. Although a few hours of low load testing were conducted, the results are considered entirely non-representative and are not presented. Note that because the unit was operated at a relatively steady, near-full load around the clock, a relatively large number of hours of data are available for the full load conditions.

The fabric filter air-to-cloth ratio for this test period averaged 2.0:1 which was the desired value. This is somewhat different from the low sulfur coal tests, where the averages were well below desired levels. There are two reasons for this improved agreement between desired and actual values. First, the load was maintained at relatively constant levels during the high sulfur coal tests. Once the correct number of fabric filter compartments was put on line, the correct number was in service virtually around the clock. Additionally, the relationship between flue gas flow rate and spray dryer roof gas disperser pressure drop, which was the relationship used to establish the number of compartments required on-line, more closely agreed with the manual measurements from the high sulfur coal portion of this program.

Figure 7-3 is a trend plot of the first week of high sulfur operation, with a 90 percent SO_2 removal set point and a nominal 2:1 air-to-cloth ratio at the fabric filter. As in Figures 7-1 and 7-2 before, system SO_2 removal, flue gas flow rate (as a percent of design gas flow), approach temperature, recycle ratio, and reagent ratio are plotted. The recycle ratio and reagent

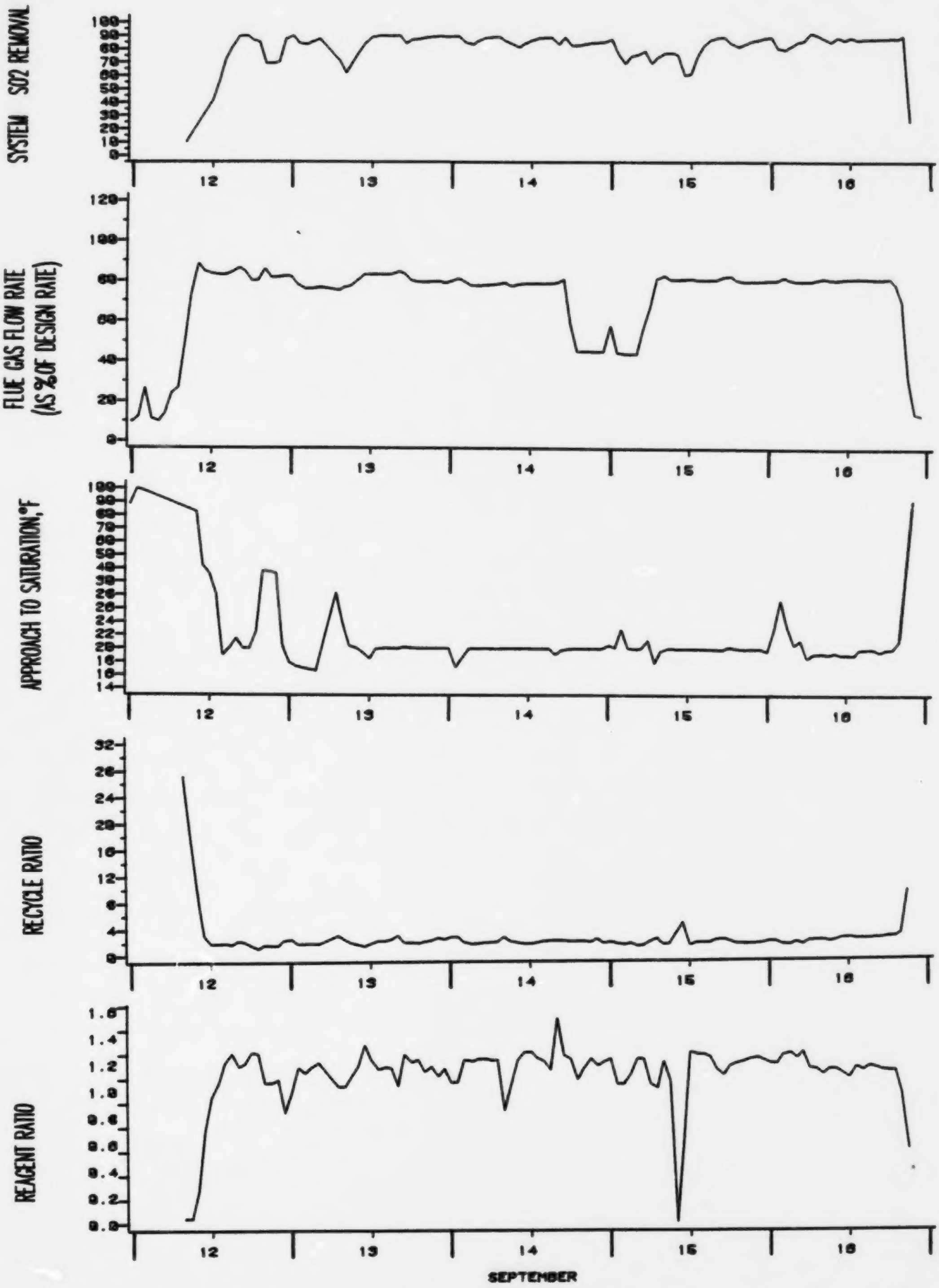

Figure 7-3. Trend plot of major system parameters during one week of high sulfur coal operation.

ratio values plotted are based on weigh belt rate measurements for quicklime to the slaker and recycle solids to the mix tank. These weigh belt values are indicative of control system responses to changes in operating conditions.

The plots indicate system start up on Monday morning through shut down Friday evening. Relatively few upsets occurred during this week. Most noticeable in these plots is that the unit load was relatively constant throughout the week, as indicated by the relatively constant flue gas flow rate. Unit load was significantly reduced only one night during this week. This change in mode of unit operation to constant load 24 hours per day was mentioned previously. The high sulfur coal firing characteristics prevented operating at less than approximately 60 MW without taking one boiler off-line. This approach of taking one boiler off-line was tried on the night of September 14th through the morning of September 15th. This period is indicated by reduced flue gas flow in Figure 7-3. Although the SO_2 removal plot in this figure is confounded by another upset to be discussed later, system SO_2 removal performance was reduced for 13 to 15 hours when the one boiler was brought off-line and then started up the next morning. Consequently, it was decided that more efficient utilization of the limited amount of high sulfur coal purchased specifically for these tests could be realized by operating at constant load around the clock from Monday morning through Friday evening.

Another difference between the low sulfur and high sulfur test periods, seen when comparing Figure 7-3 with Figures 7-1 and 7-2, is that lower flue gas flow rates (lower boiler loads) were encountered during the high sulfur tests. Boiler loads were limited during the high sulfur tests by lime slaking rate limitations, because the FGD system was not really designed to treat flue gas from high sulfur coal firing on a full-time basis. In spite of the load limitation implemented, it is apparent that the results of this test program are slightly skewed by this slaking rate limitation.

The reagent ratio values plotted in Figure 7-3 are based on quicklime weigh belt measurements and are indicative of the rate at which lime is made up to the system. Notice that with few exceptions the hourly average reagent ratio values based on lime feed for that hour are truncated around a value of 1.3 to 1.4. This is the effect of the limitation on the rate at which lime could be slaked, because of a limitation imposed by the slaking water piping sizes. Note that the overall system SO_2 removal in Figure 7-3 also appears to be truncated at a value of around 90 percent. This is also an effect of the slaking rate limitations, as the system control had little spare lime slaking capacity to allow an overshoot above the set point when recovering from an upset which caused the removal levels to be decreased. Instead, system removal tended to asymptotically approach the set point SO_2 removal after a period of maximum lime slaking rates. These limitations no doubt contributed to the average SO_2 removal for this test period reported in Table 7-10 being nearly two percent below the set point.

Only a few upsets on this trend plot need to be discussed. On the evening of September 12th, not long after 90 percent SO_2 removal was achieved after unit start up, flow of recycle material was lost when a recycle blow pot plugged. At about 2000 (8 p.m.), the approach temperature was raised to approximately 40°F as the solids level in the atomizer feed dropped. This lowered overall SO_2 removal to approximately 70 percent for 3 hours. Early the next morning, approximately 0700 (7 a.m.) on the 13th, the quicklime feed bin inadvertantly was allowed to go empty. This brief loss of lime feed caused the system SO_2 removal to drop to as low as 60 percent by 0800 (8 a.m.) before recovering.

Another upset occurred at approximately 1000 (10 a.m.) on September 15th, shortly after the banked boiler described earlier was brought back on line. In this upset, the quicklime feed weigh belt tripped out and interupted lime feed to the system for about 1 1/2 hours. System SO_2 removal again dropped to around the 60 percent level until lime feed could be reestablished.

The final upset during this week of operation occurred approximately 0100 (1 a.m.) on the 16th. At this time, one of two wet bulb monitors in service ran dry, causing the control scheme to revert to constant outlet temperature control. The control operator neglected to restore approach temperature control, and the system approach temperature varied between 28 and 18 degrees above saturation for several hours. These variations caused the system SO_2 removal to fall as low as a nominal 80 percent for 3 hours during the early morning.

As can be determined from the figure, a relatively high percentage of the system operating hours in this week were at desired conditions. Of 97 hours of system full load operation, 72 hours were at desired conditions and were used in the test averages in Table 7-10. Of the 25 full load hours not used, approximately one-third were lost during start up at the beginning of the week, and the remainder involved the various upsets described above. Figure 7-4 illustrates which hours of data were used in the averages presented in Table 7-10.

High Sulfur Tests With Calcium Chloride Addition

A second test series was conducted during high sulfur coal operation. This test series involved the addition of calcium chloride ($CaCl_2$) to the atomizer feed as a lime reagent performance enhancer. Calcium chloride has been reported in previous literature (1,2) to significantly improve lime reagent utilization in spray dryer-based FGD systems when added in sufficient quantities. The benefits are reported to result from the deliquescent properties of calcium chloride. That refers to a salt that not only absorbs moisture from the flue gas, but consequently dissolves in the absorbed moisture. In the spray dryer, this property slows droplet evaporation, allowing more time for liquid phase SO_2 removal reactions. In the fabric filter, this same property results in higher residual moisture levels in the solids collected on the bag surfaces. As described in the literature referenced above, higher residual moisture levels in turn enhance SO_2 removal reactions on the surface of the particles.

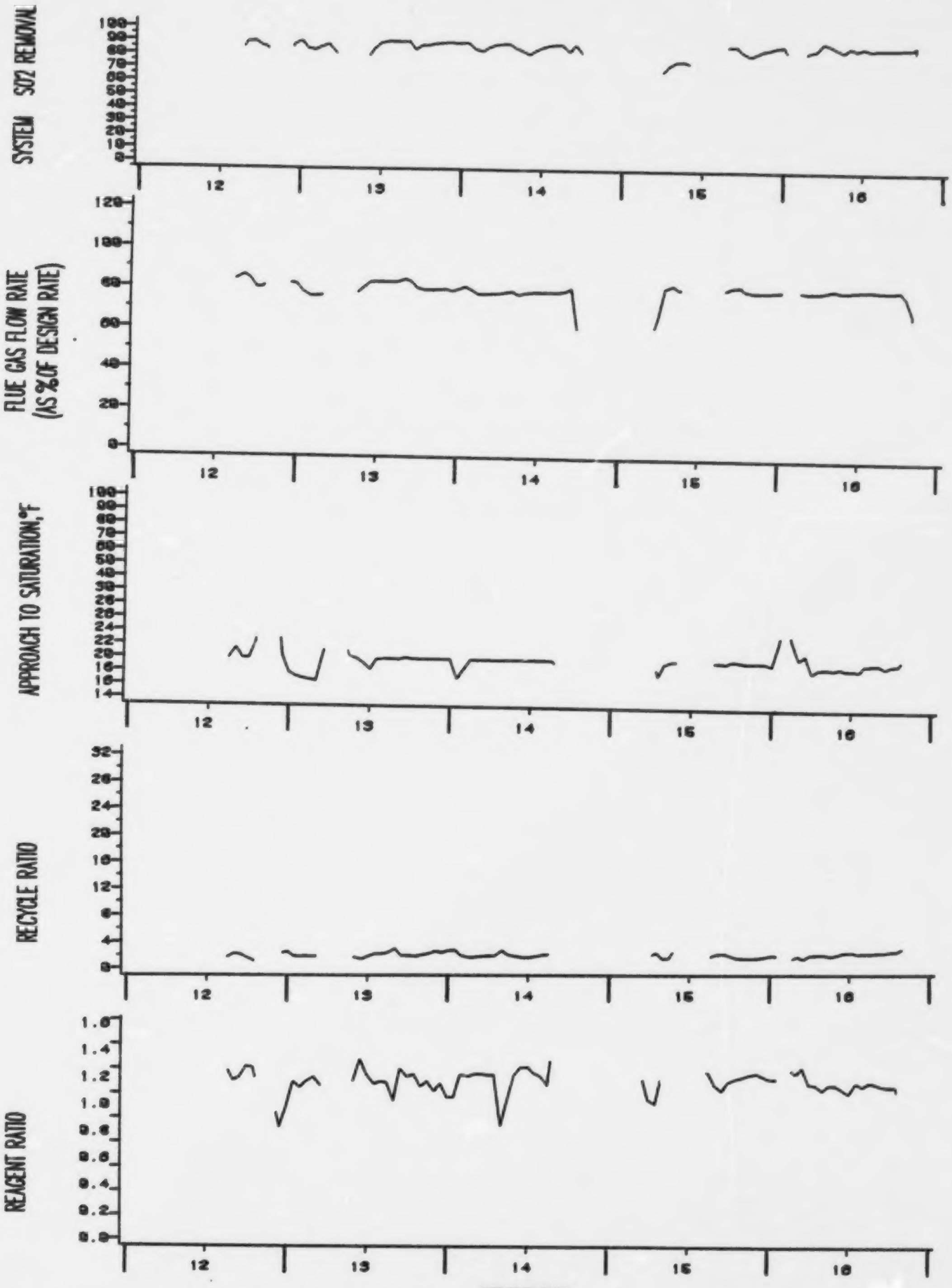

Figure 7-4. Trend plot of major system parameters during one week of high sulfor coal operation, edited to show only data used in test averages.

The calcium chloride addition levels tested were chosen to result in a 1 percent chloride content in the fabric filter solids. This level was recommended by one of the system vendors, Niro Atomizer, as being an optimum derived from pilot-scale testing at their Copenhagen, Denmark facility. For the specifics of the Riverside system (sulfur level, spray down temperature, inlet grain loading, atomizer feed solids content, etc.), this chloride content in the fabric filter solids was achieved at a chloride ion content in the atomizer feed slurry liquor of approximately 7000 ppm. Of the 7000 ppm in the liquid phase, approximately half was added as fresh makeup and the remainder was returned to the mix tank with recycle material.

The results of the calcium chloride addition test are summarized in Table 7-11. The results show that SO_2 removal averaged less than 1 percent below the set point. The reason for this improvement is that the lower reagent ratio requirement for these conditions (reduced to 0.98 from 1.33) resulted in ample lime slaking rate availability. This reagent ratio amounts to approximately a 25 percent reduction in lime requirements while adding calcium chloride.

The average spray dryer inlet temperature, approach temperature, and flue gas flow rate for the calcium chloride addition test are very nearly the same as values encountered in the baseline high sulfur coal test period. Due to the reduced reagent ratio requirements during the calcium chloride addition tests, the recycle ratio is slightly higher in spite of a slightly lower average atomizer feed solids content. The average relative accuracy for energy balances for these data is an acceptable -2.7 percent. The standard deviation about this average, 5.6 percent, is somewhat high, but still acceptable.

An interesting result of this test is the change in the individual contributions of the spray dryer and fabric filter to the overall system SO_2 removal when calcium chloride was added. The fabric filter contribution to overall removal increased to an average of 27 percent, up significantly from

TABLE 7-11. TEST RESULTS FOR THE HIGH SULFUR COAL 90% REMOVAL SET-POINT TESTS WITH CALCIUM CHLORIDE ADDITION

Parameter	Mean Value	Standard Deviation	Number of Hours of Steady-State Data
Test Results			
Overall SO_2 Removal (percent)	89.4	1.5	61
Spray Dryer Removal (percent)	62.0	4.2	59
Fabric Filter Removal (percent)	27.4	4.5	59
Reagent Ratio	0.98[a]	0.10	61
Test Conditions			
Spray Dryer Inlet Temperature (°F)	328	56	61
Approach to Adiabatic Saturation (°F)[b]	20[b]	0.4	61
Spray Dryer Inlet Flue Gas Flow Rate (acfm)	417×10^3	22×10^3	61
Percent of Design Flue Gas Flow Rate	83	4	61
Solids in Atomizer Feed Slurry (weight percent)	25	4	61
Recycle Ratio	3.2:1[c]	0.4:1	61
Relative Accuracy of Energy Balance Calculations (percent)	-2.7	5.6	61
Flue Gas Residence Time in Spray Dryer Vessel (seconds)	14	-	61
Fabric Filter Air-to-Cloth Ratio	2.0:1[d,e]	0.4:1	71

[a] Based on lime slurry solids content and feed rate

[b] Based on adiabatic saturation temperature measured at the fabric filter outlet

[c] Based on ratio of recycle material introduced at mix tank to lime solids (dry basis) in lime slurry makeup to mix tank

[d] Actual arithmetic mean calculated for hours averaged differs from desired nominal value

[e] Gross ratio, ignores effects of taking compartments off-line for cleaning and ignores reverse gas flow

16 percent in the base high sulfur coal tests. Based on the SO_2 concentration at the fabric filter inlet, SO_2 removal across the fabric filter increased to 72 percent during this test period. This indicates that the increased residual moisture levels in the fabric filter product resulting from calcium chloride addition had a significant promoting effect on the rate of SO_2 removal on the fabric filter surfaces. During the calcium chloride tests, the residual moisture levels in the fabric filter product increased from an average of 0.9 percent to approximately 1.8 percent. This amounts to a doubling of residual moisture levels during calcium chloride addition. The impacts of calcium chloride addition on spray dryer SO_2 removal rates cannot be quantified with these data. No baseline SO_2 removal data for these sulfur levels and for a 0.98 reagent ratio were measured. However, it appears qualitatively that calcium chloride addition had a greater impact on fabric filter SO_2 removal than on spray dryer removal.

One question concerning these tests results is: what commercial use does calcium chloride enhanced lime reagent have? The primary consideration is whether or not calcium chloride addition is cost effective. In these tests at Riverside, the baseline chloride content in the atomizer feed liquor was around 300 ppm. Thus, over 95 percent of the chloride in the system was spiked as calcium chloride to achieve liquid phase levels of around 7000 ppm. In considering the economics of calcium chloride addition at Riverside, it is probably not appropriate to base the economics on the actual cost of calcium chloride for these tests. Calcium chloride was purchased and shipped as a 30 weight percent solution for these tests in order to minimize set up and handling requirements. Injection required only the addition of a small, skid-mounted metering pump, a rotameter, and approximately 100 feet of flexible tubing to pump 30 percent calcium chloride solution from a rented tanker trailer used for storage on site. However, while expedient for short-term tests, this approach would not be the lowest cost approach for long-term use. In shipping the calcium chloride solution, 70 percent of the freight charges obviously go toward handling the water in the solution. As freight charges constitute a significant portion of delivered calcium chloride costs, it would probably be more economical in most locations to purchase the calcium chloride as an 80 percent purity dry flake material. The remaining 20 percent of this dry flake material is predominantly waters of hydration, which should have little impact on the effectiveness of calcium chloride added in this manner.

In these tests, the addition of calcium chloride to the 7000 ppm level in the atomizer feed slurry liquor, including chlorides dissolving from the recycle material, resulted in approximately a 25 percent reduction in lime requirements. For the 3.0 to 3.4 percent high sulfur coal, at a reagent ratio of 1.33, approximately 3.5 tons of quicklime were consumed each hour when the unit was at a 65 to 70 MW load. When adding calcium chloride, lime consumption was reduced by approximately 0.9 to 1.0 ton per hour. At the $70 per ton delivered cost of quicklime for the Riverside station, adding calcium chloride resulted in a savings of approximately $64 per hour.

During these tests, calcium chloride was added at a rate of 34.2 lb/hr, on a pure ingredient basis. A recently quoted bulk price for calcium chloride flake, at an 80 percent purity, was $145 per ton (3). Assuming freight on the calcium chloride flake would be approximately the same as that for the quicklime delivered on site, or approximately $35 per ton, the delivered cost of calcium chloride on a pure ingredient basis would be $225 per ton. At this cost per ton, the calcium chloride added during these tests would have cost approximately $38 to $49 per hour. At this cost per hour, the net savings in lime costs would have been $25 per hour. For 7000 hr/yr of operation, this savings would amount to $175,000 per year for a unit the size of that at the Riverside station.

Of course, the amortized cost of calcium chloride addition storage, mixing, and metering equipment would have to be subtracted from the net savings in delivered reagent costs. However, these calculations do illustrate the potential economic incentive for calcium chloride addition. For a larger system or higher sulfur content in the fuel, calcium chloride enhanced lime reagent could be even more attractive as a reagent for a spray dryer/baghouse-based dry FGD system.

Chlorides introduced to the system in forms other than as calcium chloride are expected be as effective in promoting lime utilization. For example, chlorides in the coal burned or in system makeup water would potentially provide the same enhancement benefits as those observed in these tests. In the absence of high concentrations of cations such as sodium or magnesium in a system, chlorides absorbed from the flue gas would be precipitated from evaporating droplets as calcium chloride. For the 3.0 to 3.4 percent sulfur coal burned in the Riverside high sulfur tests, a 0.3 percent coal chloride content would have resulted in the same 7000 ppm liquid phase chloride concentration as that achieved by calcium chloride spiking. Of course, 0.3 percent is a relatively high coal chloride content; the coal burned at Riverside had only approximately a 0.01 to 0.03 percent content. However, some high chloride content, high sulfur coals are available in the U.S. These coals are largely unsuited to units that employ wet FGD for flue gas sulfur removal, because of the negative impacts of high liquid phase chloride levels on system chemistry and metallurgy, but may be very well suited to units with spray dryer-based dry FGD.

Other aspects of chloride enhancement must be considered. First is the obvious concern about chloride effects on corrosion. The second is the question of the impacts of high chloride ion effects on solid waste disposal characteristics. Finally, the ability of the spray dryer to continue to produce dry solids when chlorides are added must be considered.

Due to the short-term nature of these tests, the impact of chloride addition on system corrosion could not be evaluated. In approximately two weeks of testing, no profoundly negative impacts were observed. However, the 7000 ppm liquid phase chloride level involved in these tests was not exceptionally high considering that some closed loop wet FGD systems may see concentrations as high as 30,000 ppm or greater. In closed loop wet systems, chlorides are only purged with the water associated with the waste sludge leaving the system. In dry FGD systems, chloride leaves the system as nearly dry chloride salts and does not concentrate as high in the liquid phase.

Also, wet FGD systems may see slurry pH levels of 4.0 to 5.0 in scrubber bottoms locations and even lower on wetted mist eliminator surfaces, wet/dry interfaces near by-pass reheat locations, stack drains, etc. In spray dryer-based FGD systems, the slurries handled are at high pH levels (11 to 12 or greater) in mix tanks, atomizer feed tanks, etc., and should have a much lower corrosion potential. Slurry droplets see low pH levels as they dry and react with SO_2, but are suspended within the spray dryer at this point. Solids leaving the spray dryer are virtually dry (3% moisture or less). The only other points where wet metal surfaces may be encountered could be if condensation occurs on fabric filter compartment walls, outlet plenums, stack liners, etc. However, these surfaces are all on the clean side of the fabric filter, so few chloride-containing solids should be encountered. However, these locations can be considered as potential sites of chloride corrosion, particularly if condensate collects near a pinhole bag fabric leak. At such a location, a low pH condensate would collect, into which chloride in the leaked particulate would readily dissolve.

Based on laboratory solid waste characterization tests conducted as part of this test program, the presence of one percent chloride in the waste solids as a highly soluble calcium salt does appear to negatively impact some waste disposal characteristics. These results are discussed in Section 9.

During the chloride addition tests, the spray dryer was continued to be operated at an 18°F approach to adiabatic saturation (20°F approach to adiabatic saturation based on the flue gas wet bulb temperature measured at the fabric filter outlet). As expected, chloride addition at the level tested raised the residual moisture level in the material which dropped out in the bottom of the spray dryer from a nominal 1.5 percent moisture to just below 3 percent. Even at this increased level of moisture, the solids were easily handled by the spray dryer recycle solids handling system. However, due to the reduced loads during this portion of the test program, the flue gas residence time in the spray dryer vessel averaged 14 seconds. This increase in residence time above the design value of between 10 and 12 seconds may have contributed to the absence of drying problems during these tests.[*]

7.2 GAS PHASE SULFURIC ACID REMOVAL RESULTS

Actually, gas phase sulfuric acid (SO_3) removal across the spray dryer/baghouse system was not directly measured. Flue gas SO_3 concentrations were measured using manual methods at the spray dryer inlet and fabric filter outlet locations. Predominantly, spray dryer inlet and fabric filter outlet measurements were conducted on the same day, but not necessarily simultaneously. This sampling approach was intended to reduce manual sampling manpower requirements. The approach was based on the assumption that in a long-term test program such as this, where operating conditions were held relatively constant for periods of one to four weeks, the values measured would not vary significantly. Considering the widely fluctuating boiler loads encountered, particularly during the low sulfur coal tests, this may not have been a valid assumption.

No spray dryer outlet location sulfuric acid concentration measurements were ever successfully completed, although measurements were attempted on several occasions. The controlled condensation technique used to measure SO_3 concentrations involves withdrawing a flue gas sample through a particulate filter heated to 500°F, then into a condenser chamber maintained below the anticipated acid dew point, but above the pure moisture (water) dew point. At the spray dryer outlet location, the high solids loadings would plug and eventually burst the particulate filter before any acid condensate was collected. If any SO_3 was present at this location, it is quite likely that it was removed by the alkaline particulate collected on the filter. The controlled condensation technique employed is further described in Appendix A.

Flue gas SO_3 concentration measurements at the spray dryer inlet and fabric filter outlet locations consistently indicated extremely low concentrations during the low sulfur test period. In spite of withdrawing relatively large flue gas samples, sulfate concentrations in the condenser catch at the spray dryer inlet location were always at or below detection limits. Calculated flue gas SO_3 concentrations were well below 0.1 ppm. At the fabric filter outlet location, virtually no trace of flue gas SO_3 content was found.

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[*] See Joy/Niro comments in Appendix F.

For the spray dryer inlet location, it could not be determined whether SO_3 formed in the boiler furnace was removed by the highly alkaline Sarpy Creek Ash, or whether only a measurement phenomenon of SO_3 removal by the sample train particulate filter was observed. At the fabric filter outlet location, the flue gas was essentially particulate-free. At this location, it was more conclusive that there was virtually no SO_3 present in the flue gas.

Results of flue gas SO_3 concentration measurements are summarized in Table 7-12. Excluding one data point which appears to be in error, the spray dryer inlet measurements varied from 1.8 to 6.3 ppm SO_3 concentrations. Using the correlations of Banchero and Verhoff (4), these concentrations result in calculated acid dew point values for the inlet gas of 244 to 267°F. The measured concentration values vary by greater than a factor of three. It is not clear whether this is due to measurement problems, or whether the actual concentrations varied over this range due to minor changes in furnace excess air levels, coal sulfur forms, or other potential variables not measured.

At the fabric filter outlet locations, measured SO_3 concentrations are all below 1 ppm, varying from 0.1 to 0.5 ppm. The first three data points listed appear to be inaccurate due to sample train leaks. Only a single value of 0.5 ppm exceeds the predominant measurements of 0.1 to 0.2 ppm as SO_3. Existing acid dew point predictive correlations are not accurate at very low flue gas SO_3 concentrations. The correlations of Banchero and Verhoff referenced above predict acid dew point values of 206 to 228°F. However, the authors state that experimental data suggest that the correlation predicts 4 to 7°F low in this range of SO_3 concentration. It is

TABLE 7-12. SUMMARY OF SULFURIC ACID CONCENTRATION MEASUREMENTS DURING HIGH SULFUR COAL TESTS

Date	Daily Run No.	Flue Gas SO_3 Conc. (ppm)	Flue Gas Moisture Content (vol. %)	Calculated Acid Dew Point (°F)[c]
Spray Dryer Inlet Results				
9/15	1	3.9	6.7	255
9/16	1	4.0	7.3	257
9/21	1	2.6	6.9	249
9/21	2	3.3	6.8	253
9/27	1	1.0[a]	7.5	---
9/27	2	2.3	5.9	244
9/29	1	1.9	7.9	246
9/29	2	1.8	8.9	248
10/3	1	2.0	7.5	246
10/3	2	6.3	7.8	267
Fabric Filter Outlet Results				
9/22	1	0.2[b]	5.0[b]	---
9/22	2	0.1[b]	3.2[b]	---
9/22	3	0.1[b]	1.9[b]	---
9/23	1	0.5	10.9	228
9/27	1	0.2	12.2	217
9/27	2	0.2	12.0	216
9/28	1	0.1	12.1	206
9/28	2	0.1	12.3	207
9/29	1	0.1	12.5	208
9/29	2	0.2	12.5	217

TABLE 7-12 (continued)

Date	Daily Run No.	Flue Gas SO_3 Conc. (ppm)	Flue Gas Moisture Content (vol. %)	Calculated Acid Dew Point (°F)[c]
10/3	1	0.1	13.3	209
10/3	2	0.2	13.8	219

[a] Suspected bad data due to broken filter in sampling train

[b] Suspected bad data due to sample proble leak

[c] Based on correlations presented in Reference 4

interesting to note that the calculated acid dew point values are above the actual flue gas temperature at the fabric filter outlet location.

Sulfuric acid removal across the system can only be indirectly quantified. Only five successful inlet SO_3 concentration measurements, on 9/27, 9/29, and 10/3, have corresponding fabric filter outlet SO_3 concentration values. These five inlet values range from 1.8 to 6.3 ppm, while the corresponding outlet values vary between 0.1 and 0.2 ppm. These data are interpreted as indicating sulfuric acid removal efficiencies of 90 percent or greater. However, considering both the variation in the spray dryer inlet concentration and the limited number of data, these results cannot be considered conclusive.

7.3 PARTICULATE REMOVAL RESULTS

As with the sulfuric acid removal results, particulate removal can only be evaluated on the basis of individual manual measurements. Flue gas particulate loading measurements were made at the spray dryer inlet, spray dryer outlet, and fabric filter outlet loactions. Also, like the sulfuric acid concentration measurements, particulate loading measurements were not generally made at two locations simultaneously. However, unlike the sulfuric acid concentration measurements, the particulate loading measurements were found to be quite consistent from measurement to measurement. Consequently, particulate removal calculations can be made with greater confidence. Also, particulate emission control regulations are generally written in terms of pounds of particulate emissions per million Btu of heat input to the source boilers; thus each individual outlet loading measurement can be used to calculate an emission rate independent of inlet loadings.

The results of particulate mass loading measurements made during the low sulfur coal test period are summarized in Table 7-13. The results in this table show that the mass loading at the spray dryer inlet varied from 3.2 to 4.1 gr/dscf and averaged 3.6 gr/dscf. Neglecting the suspected incorrect value noted in the table, the spray dryer outlet loading varied

TABLE 7-13. RESULTS OF PARTICULATE MASS LOADING MEASUREMENTS DURING LOW SULFUR COAL TEST CONDITIONS

Sampling Date	Flue Gas Mass Loading (gr/dscf)	Flue Gas Moisture Content (vol. %)	Calculated Emission Rate (lb/10^6 Btu)[a]
Spray Dryer Inlet Location			
7/12	3.6	9.6	--
7/18	3.2	10.2	--
7/19	3.2	10.7	--
8/1	4.1	9.8	--
8/22	3.9	10.4	--
8/23	3.8	10.3	--
Average	3.6	10.2	--
Spray Dryer Outlet Location			
7/29	11.0	15.8	--
8/5	13.8	16.8	--
8/15	8.3[b]	14.6[b]	--
8/16	10.9	15.9	--
8/17	11.8	16.5	--
Average	11.9[c]	16.3[c]	--

Continued

TABLE 7-13 (Continued)

Sampling Date	Flue Gas Mass Loading (gr/dscf)	Flue Gas Moisture Content (vol. %)	Calculated Emission Rate (lb/10^6 Btu)[a]
Fabric Filter Outlet - 6 (South) I.D. Fan Inlet			
7/28	0.001	15.2	0.002
7/29	0.001	16.0	0.002
8/2	0.003	13.3	0.007
8/10	0.001	14.6	0.003
8/17	0.001	15.3	0.002
8/19	0.001	15.6	0.002
Average	0.001	15.0	0.003
Fabric Filter Outlet - 7 (North) I.D. Fan Inlet			
7/27	0.002	15.6	0.006
7/28	0.002	15.3	0.005
7/29	0.001	15.8	0.002
8/2	0.002	14.9	0.005
8/10	0.001	14.6	0.003
8/17	0.002	14.8	0.005
8/19	0.003	15.5	0.007
Average	0.002	15.2	0.005

[a] Calculated by $E = C \times F\ [20.9 \div (20.9 - O_{2F.G.})]$, where C is the flue gas particulate loading in lb/dscf, F was calculated from coal analyses at 9830 dscf/10^6 Btu, and $O_{2F.G.}$ is the oxygen content (volume percent) of the flue gas at the location of the particulate loading measurement.

[b] Bad value, atomizer feed trip during sampling run

[c] Excluding value noted in b above

from 10.9 to 13.8 gr/dscf and averaged 11.9 gr/dscf. The data show that the mass loading at the spray dryer outlet (fabric filter inlet) is approximately 3 to 4 times that at the spray dryer inlet, due to the solids introduced at the spray dryer and flue gas SO_3 sorbed.

The fabric filter outlet was sampled at two locations, because the only suitable sampling locations were in the duct work after the outlet stream split to go to two separate induced draft fans and the original Unit 6 and Unit 7 stacks. Both sampling locations saw individual grain loadings between 0.001 and 0.003 gr/dscf. Both locations also averaged between 0.001 and 0.002 gr/dscf. This range of outlet loadings corresponds to particulate collection efficiencies of 99.97 to 99.99 percent, based on the average inlet loading.

Emission rates were calculated from each of the fabric filter outlet grain loading values. The rates were calculated by the following equation:

$$E = C \times F \times \frac{20.9}{20.9 - O_{2F.G.}} \qquad (7\text{-}6)$$

E is the emission rate in $lb/10^6/Btu$, C is the outlet mass loading converted to lb/dscf, and F is an emission factor, calculated as 9830 $dscf/10^6$ Btu from coal ultimate analyses using an equation specified in sub-part 60.45 of Title 40, Chapter 1 of the Federal Register (5). The last term is a correction factor to convert the mass loading data to a zero percent excess oxygen level. The term $O_{2F.G.}$ is the oxygen content of the flue gas measured during the loading determination.

The calculated emission rates vary from 0.002 to 0.007 lb/10^6 Btu. The largest of these values is still less than one-fourth of the 0.03 lb/10^6 Btu emission limit imposed by the current New Source Performance Standards for utility boilers. The smallest is more than an order of magnitude below the limit.

The results of particulate mass loading measurements during the high sulfur coal test period are summarized in Table 7-14. The results show spray dryer inlet mass loadings of 2.8 to 4.1 gr/dscf, with an average of 3.1 gr/dscf. This is very similar to that for the low sulfur coal test period, which averaged 3.6 gr/dscf. Coal analyses substantiate that the loadings should not differ greatly, as the low sulfur coal analyses averaged nearly 14 percent ash on a dry basis, while the high sulfur coal averaged only slightly lower at between 12 and 13 percent ash (dry basis). Also note the lower inlet moisture values for the high sulfur coal tests (7.9 to 8.7 percent moisture versus 9.6 to 10.7 percent moisture for the low sulfur tests). Again this observed difference is substantiated by analyses of the two coals, as the low sulfur coal averaged 22 percent moisture while the high sulfur coal averaged approximately 14 percent moisture.

The spray dryer outlet measurement results show mass loadings of 14.9 to 16.3 gr/dscf for an average of 15.7 gr/dscf. For the high sulfur coal tests, the mass loading at the spray dryer outlet averaged 5 times the inlet loading. This greater increase in mass loading during the high sulfur coal tests is predominantly the result of greater SO_2 pickup rates within the spray dryer, on a mass per unit volume of flue gas basis. Also, the weight percent solids in the atomizer feed slurry averaged slightly higher during the high sulfur coal tests.

The fabric filter outlet mass loading results show outlet grain loadings of 0.001 to 0.008 gr/dscf. The highest values, measured between September 16th and September 21st, were traced to bag problems in one compartment. The increase in mass loading during this time period appears to have

TABLE 7-14. RESULTS OF PARTICULATE MASS LOADING MEASUREMENTS DURING HIGH SULFUR COAL TEST CONDITIONS

Sampling Date	Flue Gas Mass Loading (gr/dscf)	Flue Gas Moisture Content (vol. %)	Calculated Emission Rate (lb/10^6 Btu)[a]
Spray Dryer Inlet Location			
9/13	3.0	7.9	--
9/13	3.0	7.9	--
9/27	4.1	10.7	--
9/28	2.8	8.3	--
9/28	2.8	8.7	--
10/4	2.9	8.2	--
Average	3.1	8.2	--
Spray Dryer Outlet Location			
9/14	14.9	13.5	--
9/22	16.1	13.9	--
9/23	15.5	13.6	--
9/28	15.9	14.1	--
9/30	15.3	15.6	--
10/3	16.3	14.3	--
10/4	15.9	14.7	--
10/4	15.9	15.7	--
Average	15.7	14.4	--
Fabric Filter Outlet - 6 (South) I.D. Fan Inlet			
9/16	0.008	13.6	0.022
9/21	0.007	13.5	0.018
9/23	0.002	13.9	0.005

TABLE 7-14 (continued)

Sampling Date	Flue Gas Mass Loading (gr/dscf)	Flue Gas Moisture Content (vol. %)	Calculated Emission Rate (lb/10^6 Btu)[a]
9/29	0.002	14.8	0.005
9/30	0.002	13.8	0.005
Average	0.004	13.9	0.011
Fabric Filter Outlet - 7 (North) I.D. Fan Inlet			
9/15	0.002	13.1	0.006
9/16	0.004	13.5	0.010
9/21	0.003	12.6	0.008
9/30	0.001	13.3	0.002
Average	0.003	13.1	0.007

[a] Calculated by $E = C \times F \, [20.9 \;\; (20.9 - O_{2F.G.})]$, where C is the flue gas particulate loading in lb/dscf, F was calculated from coal analyses at 9740 dscf/10^6 Btu, and $O_{2F.G.}$ is the oxygen content (volume percent) of the flue gas at the location of the particulate loading measurement.

been biased toward the south run of outlet ductwork. Excluding the measurements during this time period, outlet loadings were measured at 0.001 to 0.002 gr/dscf. Particulate matter collection efficiency across the fabric filter varied from a low of 99.95 percent, during the period of the bag problems, to 99.99 percent for the remainder of the measurements.

Calculated emission rates shown in Table 7-14 showed that even for the measurements made during the period when a bag problem was experienced, emission rates remained below the 0.03 lb/10^6 Btu limit imposed by current utility boiler New Source Performance Standards. The remaining values were several times lower than the standard.

Related to particulate mass loading measurements at the inlet and outlet of the spray dryer, on several occasions the rate at which material dropped out in the spray dryer bottom was measured as well. Measurements were made during both the low sulfur coal and high sulfur coal test periods. The measurements were relatively imprecise; the actual quantity measured was the rate at which the level increased in the hopper above the spray dryer recycle blow pot. This rate was converted from an increase in level in the hopper with time to a mass rate by multiplying by the hopper cross-sectional area and a density measured for a grab sample of the material. The major source of inaccuracy in this measurement was the fact that the material dumped into the hopper by the spray dryer bottoms mechanical conveyor tended to pile up in the center of the hopper rather than flow to a true level. An attempt was made to measure the level at the same spot on the side of this "pile"; however, it is still quite possible that the rates measured could be in error by as much as ±50 percent.

The measured spray dryer bottoms drop out rate has been expressed as a percentage of the rate at which solids enter the spray dryer, both as inlet particulate loading and as spray dried slurry. The results of these measurements are summarized in Table 7-15. Based on these limited number of measurements, it appears that a change to high sulfur operation and a decrease in flue gas flow rate (increase in spray dryer vessel flue gas residence time) had no net effect on the drop out rate. The first two measurements in Table 7-15 showed approximately the same 6 percent drop out rate in spite of these changes in operating conditions. The last two measurements, made during the $CaCl_2$ addition tests, showed a much higher drop out rate of 12 percent. This observation may be an effect of $CaCl_2$ addition, as the chlorides were observed to nearly double the residual moisture levels in the spray dryer drop out material over moisture levels during baseline high and low sulfur testing. The increased residual moisture levels would be expected to increase the density of these solids, increasing the likelihood of solids dropping out in the dryer bottom rather than being entrained with the outlet gas.

7.4 COMPARISON OF CURRENT RESULTS WITH PREVIOUS JOY/NIRO RESULTS AT RIVERSIDE

In the Introduction to this report, this program was described as providing the first independent evaluation of an operating utility-scale spray dryer-based dry FGD system. It is of interest, then, to compare the results from this program to results previously reported by the process vendors. SO_2 removal levels and reagent ratio values are of particular interest in these comparisons. Niro Atomizer has provided values derived in their previous demonstration testing at Riverside for comparison with the results of this EPA/ EPRI program. Results were provided for low sulfur coal firing for both 75 and 90 percent overall SO_2 removal, and for high sulfur coal firing and 90+ percent overall SO_2 removal. No comparison data for calcium chloride addition are available, as chloride addition was never previously tested at Riverside.

Previous Joy/Niro results for low sulfur coal tests at Riverside are compared to low sulfur coal test results from this test program in Table 7-16. The data provided by Niro include boiler fuel type, inlet SO_2 level, and reagent ratio required to achieve the nominal SO_2 removal levels tested during this program. Although the previous Joy/Niro low sulfur coal tests were with a Colstrip coal/coke mixture, inlet SO_2 levels were virtually the

TABLE 7-15. RESULTS OF SEVERAL SPRAY DRYER BOTTOMS DROP OUT RATE MEASUREMENTS

Coal Type	Removal (%)	Flue Gas Flow Rate (10^3 acfm)	Spray Dryer Vessel Residence Time (sec)	Spray Dryer Bottoms Drop Out Rate (% of total solids entering spray dryer)
Low Sulfur	90	527	11	6
High Sulfur[a]	88	432	13	6
High Sulfur[a]	90	422	14	12
High Sulfur[a]	90	432	13	12

[a] $CaCL_2$ Addition Tests

TABLE 7-16. COMPARISON OF THE RESULTS OF THE EPA/EPRI TEST PROGRAM WITH PREVIOUS JOY/NIRO RESULTS FOR LOW SULFUR COAL FIRING AT RIVERSIDE

	Joy/Niro Results	Results of EPA/EPRI Test Program
Test Period	1980/81	July/August 83
Boiler Fuel	Colstrip Coal/ Coke	Sarpy Creek Coal/ Coke
Inlet SO_2 Level (ppm)	700 to 900	700 to 900
Reagent Ratio for Nominal 75 percent SO_2 Removal	0.60	0.62 to 0.71
Reagent Ratio for Nominal 90 percent SO_2 Removal	0.75	0.82

same as those for this test program. The Colstrip coal/coke mixture also has a similarly alkaline ash.

The results in Table 7-16 show that Niro has reported slightly lower reagent ratio requirements to achieve the nominal 75 and 90 percent overall SO_2 removal levels tested during the low sulfur coal portion of this test program. The most obvious explanation for the slightly lower reagent ratio values reported by Niro is the fact that the Niro values were predominantly measured in short term (24 hours or less) steady-state periods, while the values reported for this program tend to include effects of system startup, recovery from upsets, etc. For example, in one 20-hour period during the low sulfur coal portion of this test program where unit operating conditions were very stable, an average SO_2 removal level of slightly higher than 74 percent was achieved at a mean reagent ratio of 0.54. This reagent value is even lower than that reported by Niro. Also, the values reported by Niro are easily within plus or minus one standard deviation about the corresponding means reported in Tables 7-2, 7-4, and 7-5, even if the effects of minor upsets on those means are not considered.

Niro has reported more extensive performance data from high sulfur coal tests at Riverside. These data are summarized and compared to the results of this program in Table 7-17. The previous high sulfur coal tests at Riverside were conducted with the same Peabody, Illinois coal burned during the high sulfur coal portion of this test program. The coal sulfur content comparison in Table 7-17 shows a virtually identical range of sulfur content in spot samples from each test period. Values for spray dryer inlet SO_2 concentration and inlet temperature, approach to adiabatic saturation, and atomizer feed slurry solids content are also very similar for the two test periods. The previous Joy/Niro tests were conducted at a flue gas flow rate at the spray dryer inlet which was approximately 15 percent greater than that during the high sulfur coal portion of this test program. However, the flue gas flow rate for the Joy/Niro test was within the range of flue gas flow rates encountered during other portions of this program. The atomizing conditions, not listed in the table, were equivalent in both sets of data.

TABLE 7-17. COMPARISON OF THE RESULTS OF THE EPA/EPRI TEST PROGRAM WITH PREVIOUS JOY/NIRO RESULTS FOR HIGH SULFUR COAL FIRING AT RIVERSIDE

	Joy/Niro Results	Results of EPA/EPRI Test Program
Test Period	Fall 1981	September 1983
Boiler Fuel	Peabody, Illinois Bituminous	Peabody, Illinois Bituminous
Fuel Sulfur Content (wt.%)	2.91 - 3.44	2.95 - 3.37
Inlet SO_2 Level (ppm, average)	1946	1972
Spray Dryer Inlet Temperature (°F, average)	315	322
Approach Temperature, (°F, average)	18	18
Feed Slurry Solids Content (wt.%, average)	32.5	30
Flue Gas Flow Rate (acfm at spray dryer inlet average)	470,000	412,000
SO_2 Removal (percent overall, average)	93.5	88.1
Reagent Ratio (average)	1.34	1.33
Baghouse ΔP (inches of H_2O, average)	3.3[a]	3.9[b]

[a] Air-to-cloth ratio not reported

[b] Gross air-to-cloth ratio 2.0:1

The performance data show that approximately a 5 percent higher SO_2 removal level was encountered during the previous Niro testing, at a virtually identical reagent ratio to the average for this program. This 5 percent difference is not insignificant, but may be attributable to two factors. First, the Niro test results reflect a relatively short-term, steady-state test period, while the results from this program reflect the effects of numerous start-ups and shutdowns, and recovery from various process upsets. For example, in one 16-hour period of very stable operating conditions during the high sulfur coal portion of this program, an average SO_2 removal of just over 90 percent was achieved at a mean reagent ratio of 1.33. This represents a 2 percent SO_2 removal increase over the average presented in Table 7-10, at a virtually identical reagent ratio, resulting soley from steady-state operation with no transient effects averaged in.

Also, the accuracy of flue gas and atomizer feed slurry measurements directly affect the reagent ratio determination. For the high sulfur coal baseline test in this comparison, the mean relative accuracy for enthalphy balance calculations was reported in Table 7-10 as -6.7 percent. This is potentially an indicator that either the actual atomizer feed slurry flow rate was lower than that measured or that the actual flue gas flow rate was higher than that indicated. Either effect would cause the reagent ratio measured to be higher than the actual reagent ratio by a similar amount. Thus, the actual reagent ratio value for this test period would be reduced to approximately 1.25 if the entire -6.7 percent correction was applied to the flow rate measurements. No enthalpy balance or standard deviation values are available for the Niro results. However, the combined effects of steady-state versus somewhat cyclic operation and a difference in reagent ratio of as much as 0.1 for the results from this program could explain the 5 percent higher SO_2 removal in the Niro tests at otherwise similar operating conditions.

The only other value compared in Table 7-17 is the fabric filter pressure drop. The pressure drop reported for the previous Joy/Niro test is approximately 0.6 inch of water less than the mean for the more recent test, in spite of a somewhat higher flue gas flow rate. However, data have not been provided to quantify other factors which could affect this pressure drop value, such as the number of compartments in service (i.e., air-to-cloth ratio) bag fabric type(s), and/or total operating time on the bags.

Joy and Niro have also previously published values for SO_3 removal across the system, and for fabric filter outlet grain loadings (6). These SO_3 removal data for high sulfur coal operation show a spray dryer inlet concentration of 3.6 ppm, and an outlet concentration of 0.3 ppm. These values, measured by the controlled condensation technique employed in this program, are in the middle of the range of values reported in Table 7-12. Also, the SO_3 removal which can be calculated from these data, 92 percent, is in almost exact agreement with the removal levels observed during this program. Joy and Niro report measureable quantities of sulfuric acid during previous low sulfur testing, whereas none were measured in this program. The explanation for the apparent discrepancy is not obvious.

The fabric filter outlet grain loading data reported by Joy/Niro from previous tests on this system indicate generally higher loadings than those measured during this program. The values reported by Joy/Niro in Reference 6 correspond to a range of fabric filter grain loadings of approximately 0.004 to 0.008 gr/dscf. During this program values measured ranged from 0.001 to 0.003 gr/dscf during the low sulfur coal test period and from 0.001 to 0.008 gr/dscf during the high sulfur coal test period. The differences in outlet loadings reported previously and those for this program may be attributable to different mixtures of bag materials in service; differences in bag conditions; the use of different, although both accepted, EPA Reference Methods to measure grain loadings; and other minor sampling protocol variations.

In summary, the comparisons in this subsection show good, but not exact agreement of the results of this independent evaluation of the performance of the Riverside system with those reported by the system vendors. Given that the values compared reflect differing lengths of unit operation and were taken 2 to 3 years apart, and considering the accuracy of process measurements at full-scale, these comparisions indicate that the results of this program confirm results previously reported by the system vendors.

7.5 REFERENCES

1. Karlsson, Hans T., et al, "Activated Wet-Dry Scrubbing of SO_2." Journal of the Air Pollution Control Association. Volume 33, No. 1, January 1983, pp 23-28.

2. Hansen, Svend Keis, et al, "Status of the Joy/Niro Dry FGD System and Its Future Application for the Removal of High Sulfur, High Chloride and NO_x from Flue Gas." Publication No. 83-JPGC=APC-8, The American Society of Mechanical Engineers, New York, NY, October 1983.

3. Chemical Marketing Report. Volume 224, No. 15, October 20, 1983, Schnell Publishing Company, Inc., New York, NY.

4. Pierce, Robert R., "Estimating Acid Dewpoints in Stack Gases." Chemical Engineering. April 11, 1977, pp 125-128.

5. Code of Federal Regulations, Title 40, Section 60.45.

6. Kaplan, Steven M., et al, "Dry Scrubbing at Northern States Power Company Riverside Generating Plant," presented at the EPA/EPRI Symposium on Flue Gas Desulfurization, Hollywood, Florida, May 17-20, 1982.

SECTION 8
PROCESS REQUIREMENTS

This section provides a summary of the raw materials and utilities required by the Riverside spray dryer/baghouse dry FGD system. Primary raw materials used include quicklime (CaO), process water, and calcium chloride (in the calcium chloride addition tests only). The only utility consumption rates presented here are for electric power used by major consumers. Instrument air and pneumatic conveying air are also used, but these rates were not measured.

8.1 RAW MATERIAL REQUIREMENTS

As mentioned above, raw material consumption rates were measured for quicklime, process water, and calcium chloride (for the calcium chloride addition test). These average rates for each test period are summarized in Table 8-1. In order to put the lime and process water consumption rates into perspective, the average inlet SO_2 levels and inlet flue gas flow rates for each test are also presented. The quicklime consumption rates show that the baseline high sulfur coal test required approximately 3.5 to 5 times the addition rate seen in the low sulfur coal tests. The chloride addition test results show that the addition of 340 lb/hr (0.17 ton/hr) of calcium chloride (on a 100 percent purity basis) resulted in approximately a 1.0 ton/hr savings in quicklime consumption.

The water consumption data shows that water makeup rates amounted to 0.27 to 0.28 gpm per thousand acfm for the low sulfur coal full-load tests. Makeup rates were up to 0.30 gpm per thousand acfm for the high sulfur tests, due partially to increased amount of water chemically bound by the lime slaking reaction. For the low load tests, water consumption was

TABLE 8-1. PROCESS RAW MATERIAL CONSUMPTION RATE SUMMARY

Coal Type	Inlet SO_2 Level (ppm)	SO_2 Removal (%)	Gross Fabric Filter A/C Ratio (acfm/ft^2)[a]	Flue Gas Flow Rate (10^3 acfm)	Quicklime Consumption (tons/hr)	Water Consumption (gpm)	$CaCl_2$ Consumption (ton/hr)
Full Load Tests							
Low Sulfur	812	74	—[b]	429	0.80	117	—
Low Sulfur	809	75	1.8:1	446	0.73	126	—
Low Sulfur	803	89	1.6:1	493	1.05	140	—
High Sulfur	1972	88	1.9:1	412	3.58	122	—
High Sulfur	2067	89	2:1	425	2.62	128	0.17[c]
Low Load Tests							
Low Sulfur	793	72	—[d]	336	0.68	89	—
Low Sulfur	752	76	1.3:1	326	0.62	88	—
Low Sulfur	764	90	1.1:1	335	0.82	84	—

[a] Excludes effects of compartments off-line for cleaning and reverse gas flow

[b] Not measured, estimated to be approximately 1.7:1 based on average fabric filter pressure drop

[c] Expressed on a 100 percent $CaCl_2$ basis. $CaCl_2$ was actually added on a 30 weight percent solution.

[d] Not measured, estimated to be approximately 1.4:1 based on average fabric filter pressure drop

reduced to 0.25 to 0.27 gpm per thousand acfm. This reduction was due to approximately a 30°F drop in flue gas inlet temperature for these tests.

8.2 UTILITY REQUIREMENTS

The only utility rates measured were for electric power consumption. The largest electric power users in the system are the atomizer drive motor and the induced draft fans which must overcome pressure losses in the spray dryer and fabric filter. Atomizer power consumption was directly measured and recorded by the Honeywell process control computer. Measured average atomizer power values, in kW, are presented for each test period in Table 8-2. Also presented in Table 8-2 are calculated horsepower values corresponding to each kW value. The horsepower values indicate that the 90 percent SO_2 removal, low sulfur coal test period, which very nearly averaged the system design flue gas flow rate of 500,000 acfm, also very nearly averaged the rated atomizer motor power value of 700 horse power.

Fan power values are presented in Table 8-3. These are calculated values, based on average flue gas flow rates and spray dryer and fabric filter pressure drops. The calculations assume an overall fan and motor efficiency of 70 percent. The flue gas flow rate and pressure drop values upon which these calculated values are based are listed as well. Fan power values were not directly measured because furnace and air heater draft losses are also overcome by these fans, and varied damper settings can also confuse fan power measurements. It should be noted that the pressure drop values measured in this program agree quite well with those used in a previous dry FGD economic evaluation (1), after being corrected to equivalent flue gas flow rate and fabric filter air-to-cloth ratio values.

Measured current values for other electric power consumers in the system are summarized in Table 8-4. The total electric power required by these electric motors is only approximately 15 percent of the atomizer power. Unfortunately, current values were not measured for several other potentially significant power demands: the baghouse and spray dryer bottoms

TABLE 8-2. AVERAGE ATOMIZER POWER REQUIREMENTS

Coal Sulfur Level	SO_2 Removal (%)	Average Slurry Feed Rate, gpm	Average Atomizer Power	
			(kW)	(hp)
Full Load Tests				
Low Sulfur	74	135	424	569
Low Sulfur[a]	75	147	471	632
Low Sulfur	89	160	503	675
High Sulfur	88	138	441	591
High Sulfur[b]	89	139	453	607

[a] Increased air-to-cloth ratio at fabric filter, all other tests at normal air-to-cloth ratio

[b] With $CaCl_2$ addition

TABLE 8-3. AVERAGE PRESSURE DROP AND FAN POWER VALUES

Coal Type	Average SO_2 Removal (%)	Average Flue Gas Flow Rate (10^3 acfm)	Gross Fabric Filter A/C Ratio (acfm/ft^2)[a]	Estimated Spray Dryer and Ductwork Pressure Drop (in. H_2O)[b]	Fabric Filter Pressure Drop (in. H_2O)[c]	Calculated I.D. Fan Power (kW)
Full Load Tests						
Low Sulfur	74	429	—[d]	3.2	4.0	439
Low Sulfur	75	446	1.8:1	3.4	4.5	502
Low Sulfur	89	493	1.6:1	4.0	3.6	535
High Sulfur	88	412	1.9:1	3.0	3.9	404
High Sulfur[e]	89	425	2:1	3.2	3.5	401

[a] Excludes effects of compartments off-line for cleaning and reverse gas flow

[b] Estimated as a function of flue gas flow rate, based on a limited number of manual duct pressure measurements

[c] Flange to flange

[d] Not measured, estimated to be approximately 1.7:1 based on average fabric filter pressure drop

[e] With $CaCl_2$ addition

conveyors, the pneumatic conveying system air compressors, and the reverse gas fan.

The values in Table 8-4 are slightly higher for the high sulfur coal tests than for the low sulfur coal tests. Lime handling power rates are somewhat higher because lime consumption for the high sulfur coal tests was approximately 3 times that for the 90 percent removal low sulfur coal test, which these low sulfur values represent. Slurry feed related power consumption is probably increased because the higher lime content in the atomizer feed slurry resulted in increased slurry viscosity.

Note that during the low sulfur coal tests, both the normal and spare lime slurry transfer pumps and the normal and spare feed slurry transfer pumps were running simultaneously. This was a temporary measure designed to reduce spare pump suction pluggage. Both atomizer feed pumps were not run because one had a higher hydraulic capacity than the other and would pump against the other when both were running. Due to these extra pumps running, the total power demand in the feed slurry preparation area was virtually identical for the two test periods, in spite of higher individual values for the high sulfur test conditions.

Several other utility requirements were not measured. These included electric power for the control computer, instruments, and controls, and instrument air used in control valves, blow pot operators, baghouse compartment dampers, and bin vents, as well as other miscellaneous electricity and air requirements.

8.3 REFERENCES

1. Keeth, R. J. et al, Economic Evaluation of FGD Systems, Volume 1: Throwaway FGD Processes, Highland Low-Sulfur Coal EPRI CS-3342, Volume 1, Research Project 1610-1. Palo Alto, CA. December, 1983.

TABLE 8-4. SUMMARY OF CURRENT MEASUREMENTS ON MINOR SYSTEM POWER DEMANDS

	Low Sulfur Tests[a] (amps @ 460V, 3ϕ)	High Sulfur Tests[b] (amps @ 460V, 3ϕ)
Lime Weigh Belt (est.)	1.5	1.5
Attrition Slaker		
Cell 1	12.5	14.2
Cell 2	13.1	13.2
Classifier	3.5	3.9
Lime Transfer Pump		
A	6.3	8.0
B	6.0	Off
Recycle Weigh Belt	1.5	1.4
Mix Tank Agitator	13.0	14.5
Recycle/Lime Slurry Transfer Pump	2 x 6.4	7.1
Feed Tank Agitator	8.5	8.5
Atomizer Feed Pump	26.5	33.0
Total Amperage	105.2	105.3
Total KVA[c]	84	84

[a] Overall removal 89%, 0.94 instantaneous reagent ratio value, 829 ppm inlet SO_2 concentration, 20°F approach to adiabatic saturation based on fabric filter outlet wet bulb temperature, 547,000 acfm inlet flue gas flow.

[b] Overall removal 91%, 1.20 instantaneous reagent ratio value, 1962 ppm inlet SO_2 concentration 18°F approach to adiabatic saturation based on fabric filter outlet wet bulb temperature 419,000 acfm spray dryer inlet flue gas flow.

[c] Reported as kVA rather than kW because the power factors for these electric motors were not measured and cannot be readily estimated.

SECTION 9
WASTE PRODUCT CHARACTERIZATION

This section describes the results of a laboratory-scale study of the waste disposal characteristics of solid waste samples collected during this program. The study has included chemical analyses of the wastes, determination of waste particle morphology through scanning electron microscope (SEM) photographs, and measurement of physical properties of cured and uncured wastes. Also, the compositions of leachates from both cured and uncured samples have been determined. Finally, the characteristics of these waste materials are compared to those for samples from other spray dryer-based dry FGD systems.

The organization of this section follows the order of the description above. Subsection 9.1 describes the operating conditions for the Riverside dry FGD system when each of the three samples studied were taken, and provides an overview of the analyses and test procedures conducted in this study. Subsection 9.2 describes the results of chemical analyses of the waste samples, including elemental concentrations, anionic species concentrations, and moisture and insoluble species contents. Subsection 9.3 provides a description of waste particle morphology, through interpretation of SEM photographs of selected samples. Physical properties of cured and uncured samples are summarized in Subsection 9.4 These properties include unconfined compressive strength and permeability. Subsection 9.5 describes the leachate quality for both EP extractions and neutral extractions of cured and uncured samples. Concentrations of elemental and anionic species and other water quality parameters are reported. Elemental species concentrations in the EP leachates are used to determine whether the wastes would potentially be classified as hazardous or non-hazardous. Finally, the results of this study are compared with previous results for waste samples from other dry FGD systems in Subsection 9.6.

9.1 DESCRIPTIONS OF SAMPLES AND TEST PROCEDURES

9.1.1 Sample Descriptions

Waste products were collected from the Riverside system baghouse (fabric filter) during three of the five test periods. One sample was collected when the fuel was the mixture of low sulfur western coal and coke usually burned at Riverside station. Two of the samples were collected when the Illinois No. 6 (high sulfur) coal was being burned. Nominal overall sulfur dioxide removal efficiencies were 75 percent for the low sulfur coal sample and 90 percent for both high sulfur coal samples. Calcium chloride was added to the feed slurry for one of the high sulfur runs. Process operating conditions at the time samples were collected are summarized in Table 9-1.

The first sample listed is for one of the low sulfur coal, 75 percent SO_2 removal set point test periods. This sample is for the test period at slightly increased air-to-cloth ratio at the fabric filter. The 75 percent removal test period was chosen for characterization because it represents the SO_2 removal level that would be required for this coal by current New Source Performance Standards (NSPS) for utility boilers. The sample is presumably typical of wastes from a spray dryer-based FGD system on a boiler firing low sulfur, alkaline ash coal. As seen in the table, sub-stoichiometric amounts of lime were being added at the atomizer when this sample was collected. Consequently little, if any, excess $Ca(OH)_2$ is present in the sample.

The second sample listed was taken during the baseline 90 percent SO_2 removal set point, high sulfur coal test. Again, 90 percent SO_2 removal is the current NSPS-mandated level for this coal. The table shows that an excess of lime was being added to achieve this removal level.

TABLE 9-1. OPERATING CONDITIONS FOR WASTE PRODUCT SAMPLES COLLECTED DURING THE RIVERSIDE SYSTEM CHARACTERIZATION PROGRAM

	Low Sulfur Coal 75% SO_2 Removal	High Sulfur Coal 90% SO_2 Removal	High Sulfur Coal With $CaCl_2$ Addition 90% SO_2 Removal
Gas Flow Rate (10^3 acfm)	402	440	433
Approach Temperature (°F)[a]	20	20	20
Reagent Ratio[b]	0.58	1.30	0.96
Recycle Ratio[c]	15.9	2.4	3.4
Inlet Temperature (°F)	338	330	330
Inlet Sulfur Dioxide Concentration (ppm, wet basis)	840	1,970	2,100
System Sulfur Dioxide Removal (%)	74	88	90
Removal in Spray Dryer (%)	64	71	64
Removal in Fabric Filter (%)	10	17	26

[a] Based on wet bulb temperature measured at fabric filter outlet, approximately 2°F lower based on wet bulb temperature at spray dryer inlet.

[b] $$\frac{\text{fresh } Ca(OH)_2 \text{ in atomizer feed, lb-mole}}{SO_2 \text{ in spray dryer inlet flue gas, lb-mole}}$$

[c] $$\frac{\text{recycle material added to mix tank, lb}}{\text{lb lime } (Ca(OH)_2) \text{ solids in lime slurry added, lb}}$$

The third sample was collected during the 90 percent SO_2 removal, high sulfur coal test with $CaCl_2$ addition. This sample was selected for study in order to evaluate what impacts, if any, chloride addition may have on solid waste disposal properties. The sample is characterized by having high chloride levels (approximately 1 percent chloride) and little excess lime present.

Each sample represents a grab sample taken over a relatively short period of time from the south conveyor emptying fabric filter compartment hoppers. As such, each may not necessarily be representative of the entire waste solids stream being collected in the fabric filter during that test period.

9.1.2 Test Procedures

The test results presented in this section provide information about:

- chemical compositions of solids and extracts from the solids;
- particle shapes and sizes; and
- other physical properties such as strengths and permeabilities of samples mixed with water, compacted, and cured.

The laboratory tests and procedures employed to provide this information are listed in Table 9-2. More complete descriptions of the tests are provided in Appendix A.

Chemical characterization of the waste products included:

- elemental analyses of solids and extracts,
- determination of soluble anionic species in solids by chemical methods, and

TABLE 9-2. SUMMARY OF TESTS AND TEST PROCEDURES FOR RIVERSIDE DRY FGD SYSTEM WASTE PRODUCTS

Parameter	Procedure
CHEMICAL COMPOSITION OF SOLIDS	
Elemental Composition	Inductively Coupled Argon Plasma Emission Spectrometry and Atomic Absorption Spectrophotometry
Hydroxide	Acid-Base Titration
Carbonate	Non-Dispersive Infrared Spectrometry
Sulfate	Ion Chromatograpny
Sulfite	Iodine Titration
Chloride	Ion Chromatography
CHEMICAL COMPOSITION OF EXTRACTS	
Elemental Composition	Inductively Coupled Argon Plasma Emission Spectrometry and Atomic Absorption Spectrophotometry
Water Quality Parameters	pH Meter, Conductivity Meter, Gravimetric Analyses
Total Sulfur as Sulfate	Ion Chromatography
Fluoride	Ion Selective Electrode
Chloride	Ion Chromatography
Nitrate	Ion Chromatography
PHYSICAL TESTS	
Strength Development	ASTM Method D-1633
Permeability	Permeameter
Particle Size and Shape	Scanning Electron Microscope
OTHER TESTS	
Moisture	Gravimetric Analysis
Insoluble Material	Gravimetric Analysis
Extractions	EP Procedure as Described in May 19, 1980 Federal Register and Identical Extraction without Acetic Acid Addition

- measurement of water quality parameters and concentrations of selected elements and anions in extracts.

Results of these measurements can be used to estimate relative amounts of major components in the solids, determine regulatory classification, and identify leachable species. Leachable species are of interest in selection of appropriate disposal practices.

Physical properties measured were unconfined compressive strength, permeability coefficients, and particle sizes and shapes. Strength measurements help predict physical stability of landfilled wastes. Permeability coefficients provide information needed to estimate the amount of leachate that may be expected under a given set of conditions. Particle sizes and shapes provide information related to potential solids compaction efficiencies.

9.2 WASTE SOLIDS CHEMICAL ANALYSES

Chemical analyses conducted on the three waste solids samples described above included determination of elemental concentrations, anionic species concentrations, and moisture, acid insoluble, and water insoluble contents. Results of each are described below.

9.2.1 Elemental Concentrations in Waste Solids

Concentrations of 29 elements present in major, minor and trace proportions are summarized in Table 9-3. The concentrations of several elements were found to vary significantly in the three samples tested. Differences in composition can be attributed to differences in fly ash composition and to differences in relative amounts of fly ash, unused reagent, and flue gas desulfurization products. Note that the calcium content of the waste products roughly correlates with the reagent ratio at which the system was operating when the samples were taken. For example, the low sulfur coal waste sample at the lowest reagent ratio of the three also has the lowest

TABLE 9-3. SUMMARY OF ELEMENTAL ANALYSES ON RIVERSIDE WASTE SOLID SAMPLES

Element	Low Sulfur Coal (μg/g)	High Sulfur Coal (μg/g)	High Sulfur Coal with $CaCl_2$ Addition (μg/g)
Aluminum	53,000[a]	33,000[a]	35,000[a]
Antimony	<20	<30	< 6[b]
Arsenic[c]	<20	<20	<11
Barium	2,900	260	210
Beryllium	0.94	1.7	1.5
Boron	ND[d]	ND[d]	ND[d]
Cadmium[c]	< 1	< 1	6.1
Calcium	160,000	200,000	180,000
Chromium	6.9	54	49
Cobalt	8.9	15	14
Copper	33	45	1.1
Iron	23,000	39,000	45,000
Lead[c]	31	48	22
Magnesium	14,000	4,600	4,500
Manganese	638	190	200
Mercury[c]	ND[d]	ND[d]	ND[d]
Molybdenum	24	29	27
Nickel	200	50	50
Potassium	7,900	8,700	9,300
Selenium[c]	<30	<50	<20
Silicon	99,000	70,000	78,000
Silver	<0.4	< 2	<0.4
Sodium	3,400	1,040	3,200
Strontium	2,000	170	240
Thallium	<30	<30	<20
Tin	<100	<100	<20
Titanium	2,900	2,400	2,500
Vandium	480	99	86
Zinc	28	210	220

[a] Analysis was by ICPES on solution prepared by lithium metaborate fusion. Other elemental concentrations in solids were determined using perchloric acid solutions.

[b] "Less than" values indicate analytical detection limit.

[c] Concentrations in extracts measured by atomic absorption spectrophotometry.

[d] Not determined because boron and mercury are lost during digestion procedure.

calcium content, while the high sulfur coal baseline test waste sample at the highest reagent ratio also has the highest calcium content. Actually the low sulfur coal sample would be expected to have a much lower calcium content based on the much lower absolute lime addition rate relative to the high sulfur tests, but the calcium content of the coal ash (see Table 7-1) significantly contributed to this total. Material balances indicate that for the low sulfur coal sample, calcium in the lime added only contributes about 30 percent of the calcium present. The calcium in the coal ash contributes the remaining 70 percent. In contrast, for the high sulfur coal baseline sample, the lime added accounts for over 90 percent of the calcium present.

Other differences in the samples are likely related to the differences in coal sulfur levels and/or ash characteristics as well. The aluminum, titanium, and silicon contents for the low sulfur coal sample were higher than those for the two high sulfur coal samples, even though these elements were present in lower concentrations in the low sulfur coal ash (see Tables 7-1 and 7-9). This apparent discrepancy is the result of the higher recycle ratio and lower flue gas sulfur levels for the low sulfur coal sample, causing the low sulfur coal sample to have a much greater fly ash content. The higher magnesium level in the low sulfur coal ash is an apparent effect of the different coal ash compositions, as the low sulfur coal ash has a magnesium content two to three times that of the high sulfur coal ash.

9.2.2 Anionic Species in Solids as Measured by Wet Chemical Procedures

Concentrations of major anionic species (carbonate, hydroxide, sulfate, sulfite, and chloride) provide measures of the relative proportions of products of side reactions, unused reagents, and products of desulfurization reactions which are present in the spray dryer waste products. The degree of oxidation of sulfite to sulfate within the system is also indicated.

In systems employing lime as the reagent, carbonate is the product of a side reaction of calcium hydroxide with carbon dioxide. The carbon dioxide may be absorbed from the atmosphere in the lime storage tank or from the flue gas in the spray dryer. Hydroxides come predominantly from unused reagent in lime systems. Sulfate and sulfite provide a measure of concentrations of products of the desulfurization reaction in the dry scrubbing waste products. Their relative proportions indicate the amount of oxidation occurring in the system. Chloride concentrations can come from chlorides in fly ash, hydrochloric acid scrubbed from the flue gas, and from the use of $CaCl_2$ as a performance additive.

The rigorous digestion procedures used to bring solid samples into solution for analysis for elemental concentrations as described above radically alter the anionic composition of the material and cannot be used for determination of anionic species. Consequently, wet chemical procedures were used to determine concentrations of anionic species in the spray dryer waste products. These techniques measure only the acid- or water-soluble portions of anionic species present. These measurements represent the best available determinations of anionic species which are present in unused reagent and in the products of the desulfurization rections. Any anions trapped in acid- or water-insoluble matrices within the fly ash component of the wastes could not be accounted for using these techniques. However, these anions would be expected to represent only a minor portion of the total in each sample.

Concentrations of soluble anionic species in the spray dryer waste products (as measured by chemical techniques) are listed in Table 9-4. Concentrations of all species measured varied significantly from sample to sample. Variations can be related to changes in process conditions and coal sulfur levels.

Carbonate values varied from 2.2 to 2.7 weight percent expressed as carbon dioxide. High values indicate a significant amount of reaction with carbon dioxide. Low values indicate that the system was operated at conditions which minimized this side reaction. Surprisingly, the carbonate levels measured did not appear to be strongly affected by the lime reagent

TABLE 9-4. CONCENTRATIONS OF SOLUBLE ANIONIC SPECIES IN WASTE PRODUCTS FROM THE RIVERSIDE TEST PROGRAM

Sample Description	Carbonate[a] (wt % CO_2)	Hydroxide[a] (wt % OH)	Sulfate[a,b] (wt % SO_3)	Sulfite[a] (wt % SO_2)	Chloride[c] (wt % Cl)
Low Sulfur Coal	2.2	<0.1	8.5	8.0	<0.1
High Sulfur Coal	2.7,2.5[d]	4.8,4.5[d]	3.1	19.0	<0.1
High Sulfur Coal with $CaCl_2$ Addition	2.7	1.0,1.0	3.0	20.5	1.0

[a] Measured by acid dissolution of sample.

[b] Sulfate was calculated as the difference between total sulfur and sulfite sulfur.

[c] Measured by water dissolution of sample.

[d] Duplicate analyses.

ratio in the atomizer feed. It might have been expected that the highest carbonate level would have been observed for the baseline high sulfur test, where the greatest amount of excess lime available for this side reaction would be expected.

An acid-base titration was carried out to try to quantify excess alkalinity. Some problems were encountered in trying to obtain reproducible results. Alkalinities to end points in the pH range 7.5 to 8.5, corrected for carbonate contribution, are reported as hydroxide. Although these results are of questionable accuracy, they do indicate the lowest excess lime levels in the low sulfur coal sample and the highest excess in the baseline high sulfur coal sample. This order would be expected based on the reagent ratio values for these tests.

Sulfate concentrations ranged from 3.0 to 8.5 weight percent calculated as SO_3. Sulfite concentrations ranged from 8.0 to 20.5 percent calculated as SO_2. These ranges represent wide variations in both the absolute amounts of FGD products present and in the degree of oxidation. As expected, products from flue gas with high SO_2 levels yielded the highest total sulfur values in the waste products. The percent oxidation results are also as expected. The high sulfur coal samples showed 10 to 12 percent oxidation, while the low sulfur coal sample showed an oxidation level of 46 percent. Experience in wet FGD systems would lead one to expect higher oxidation levels for the low sulfur coal tests. It is not obvious how chloride addition would be expected to affect oxidation levels.

Chloride concentrations were found to be dependent on the process conditions for each run. Chloride was added as a performance additive during the second of the high sulfur runs; therefore, the chloride concentration for this sample is significantly higher than in the samples from the other two runs. This analysis confirms that at least for the time period when this sample was collected the target chloride level of 1.0 percent in the fabric filter solids was achieved.

9.2.3 Moisture Content and Insoluble Fraction of Waste Solids

The free moisture content of all three samples was found to be relatively low. Moistures were determined by drying in an oven for 4 hours at $50^{o}C$. Weight losses attributable to loss of free moisture are listed in Table 9-5. As mentioned in Section 5, the addition of $CaCl_2$ as a performance additive essentially doubled the residual moisture level in the waste solids. However, even this increased moisture level is still considered quite acceptable from a solids handling quality viewpoint.

Percentages of materials insoluble in acid and in water are also listed in Table 9-5. As expected, the percentage insoluble in water is much greater for all samples than the percentage insoluble in acid. This is expected because most calcium salts produced in the spray dryer have limited solubilities in pure water but are completely soluble in hydrochloric acid. It would be expected that the low sulfur coal sample, which has the highest fraction fly ash, would also have the highest water and acid insoluble levels. However, the low sulfur coal ash has a greater portion of water soluble and limited solubility components, such as CaO, MgO, Na_2O, and SO_3. Consequently, the water and acid insoluble portions of the three sample are quite similar.

9.3 WASTE PARTICLE MORPHOLOGY

Scanning electron micrographs of the waste samples were taken to examine particle sizes and shapes. Micrographs for the low sulfur coal sample are presented in Figure 9-1. Spherical fly ash particles dominate most of the upper photomicrograph, taken at a nominal magnification of 500. The lower photomicrograph in Figure 9-1 shows a close up of one portion of the upper scan. This photomicrograph, at a nominal magnification of 5000, shows numerous spherical fly ash particles intermixed with fine crystals that are presumably the products of the FGD reactions.

TABLE 9-5. MOISTURE CONTENT, ACID INSOLUBLE CONTENT, AND WATER INSOLUBLE CONTENT IN WASTE SOLIDS FROM THE RIVERSIDE TEST PROGRAM

Sample Description	Moisture[a] to 50°C (wt %)	Acid Insolubles (wt %)	Water Insolubles (wt %)
Low Sulfur Coal	0.4	32.0	78.4
High Sulfur Coal	0.5	34.1	80.3
High Sulfur Coal with $CaCl_2$ Addition	1.1	35.4	83.0

[a] Moisture evolved at 50°C is considered to be free moisture. Waters of hydration are generally evolved at higher temperatures.

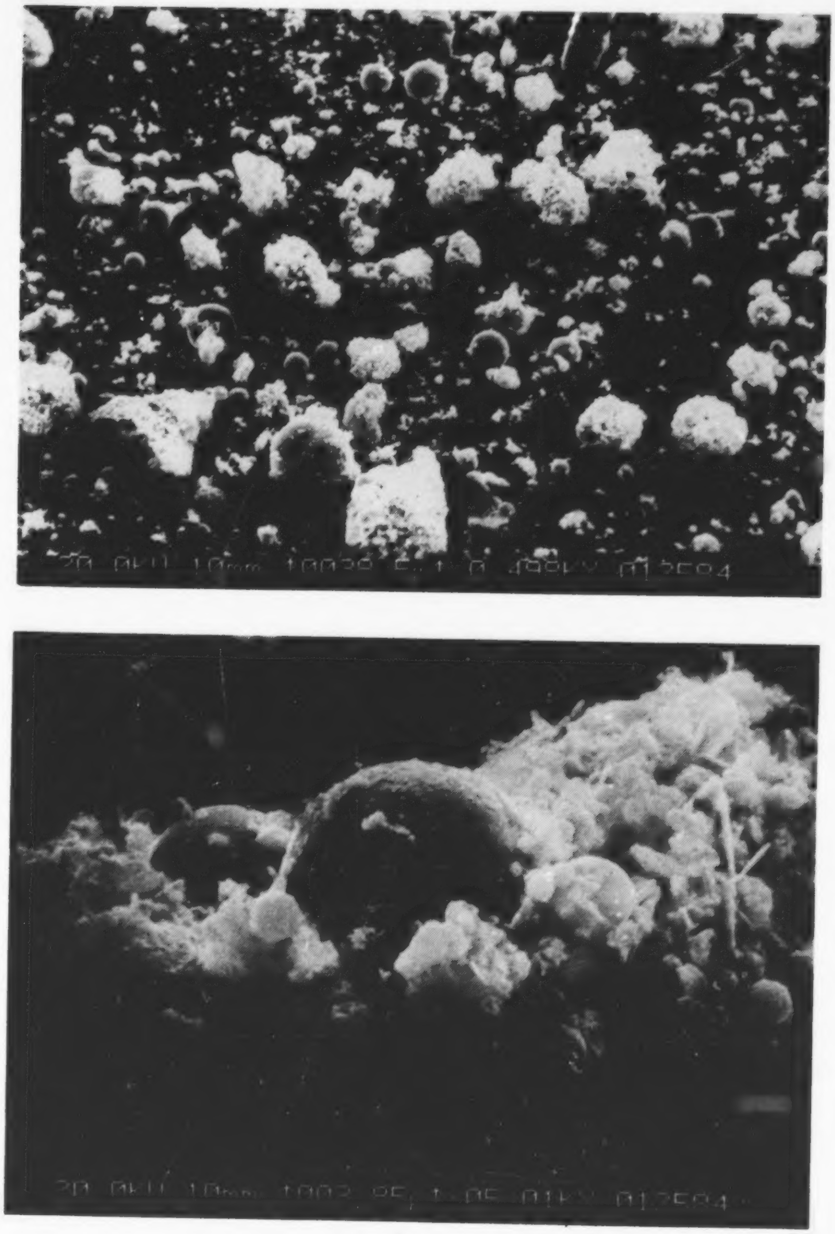

20 0KV 10mm 10029 E,1 0 499KV 012504
20 0KV 10mm 1002 95,1 05 01KV 012504

Figure 9-1. Scanning electron micrographs of spray dryer product from the baghouse during low sulfur coal test (75% removal) at Riverside station.

Figure 9-2 shows the elemental compositions at the surface of two portions of the lower photomicrograph in Figure 9-1. The photomicrograph is repeated at the top of Figure 9-2, and the points at which the two elemental scans below were taken are marked. One elemental scan (A) is for the surface of the large spherical, presumably fly ash, particle near the center of the photomicrograph. The elemental scan for point A in Figure 9-2 shows a predominance of the major elements in the low sulfur ash: alumina, silica, and calcium. Very little sulfur is present, indicating that very few by-products of FGD reactions are near this point. The elemental scan for point B confirms that the smaller crystalline material in the photomicrograph is indeed primarily FGD reaction by-products. The scan shows predominantly calcium and sulfur, with less quantities of fly ash elements such as alumina and silica. It should be noted that the gold (Au) peaks for both scans result from gold plating during the election microscope sample preparation procedure.

Figures 9-3 and 9-4 show photomicrographs of samples from the baseline high sulfur coal waste products. The upper portion of Figure 9-3 is an overview of a number of particles, at a magnification of 500. The lower portion is a photomicrograph of one particle at a magnification of 5000. Figure 9-4 shows 2000x magnifications of two other particles from the top portion of Figure 9-3. There is a noticeable difference between the particles from the low sulfur test in Figure 9-1 and these particles. In the low sulfur photomicrographs a number of smooth, spherical, purely fly ash particles were visible. In these photomicrographs of high sulfur samples, virtually all particles appear to be covered with FGD reaction products. In fact, an elemental scan of a particle similar to those seen in Figures 9-3 and 9-4, as shown in Figure 9-5, indicates a predominance of calcium and sulfur on the surface, and only minor quantities of elements present in fly ash. No fly-ash-only particles are seen in Figures 9-3 and 9-4. This observed difference relative to Figures 9-1 and 9-2 is perhaps because the samples from high sulfur coal operation have a much higher ratio of FGD reaction products to fly ash, resulting in virtually all particles being covered with FGD reaction products. However, because a statistically

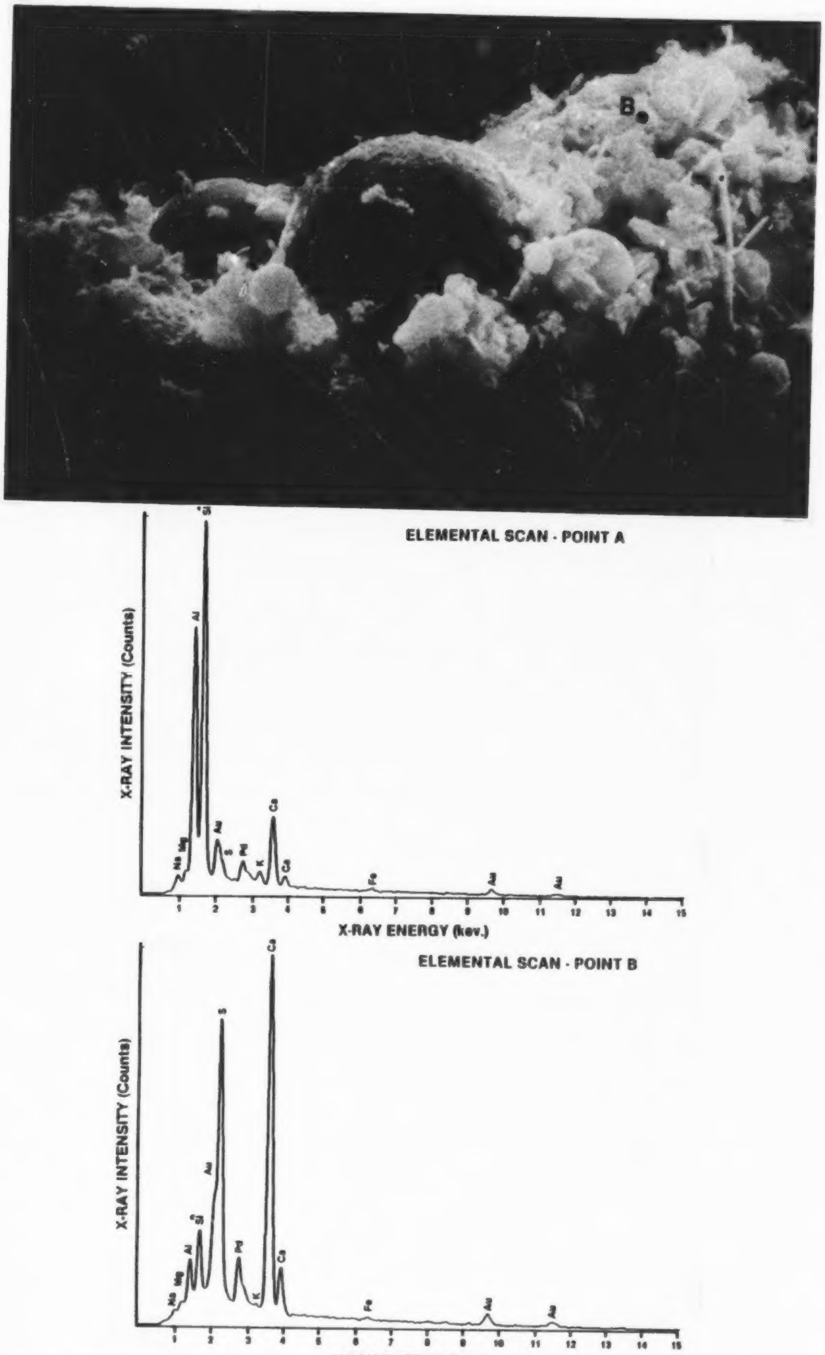


Figure 9-2. Scanning electron micrograph and elemental scans of spray dryer product from the baghouse during low sulfur coal test (75% removal) at Riverside station.

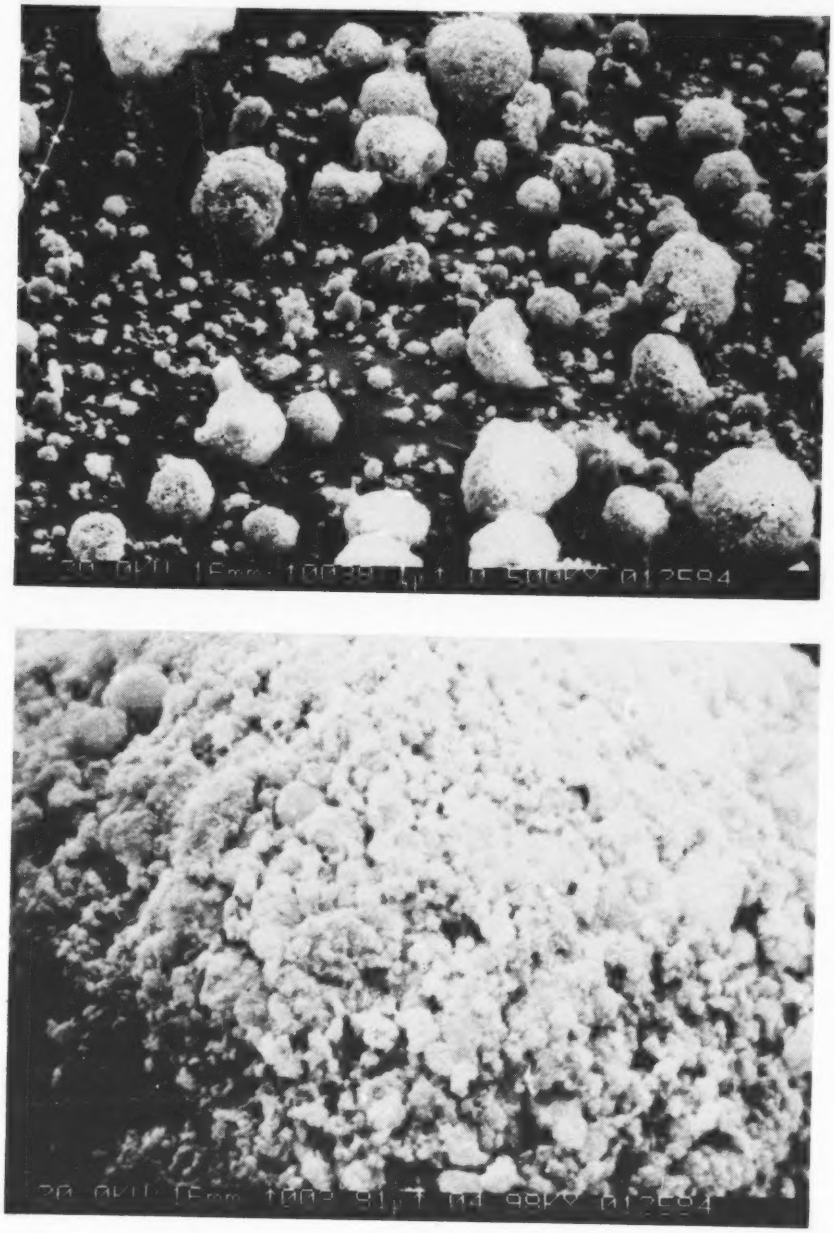


Figure 9-3. Scanning electron micrographs of spray dryer product from the baghouse during high sulfur coal baseline test (90% removal) at Riverside station.

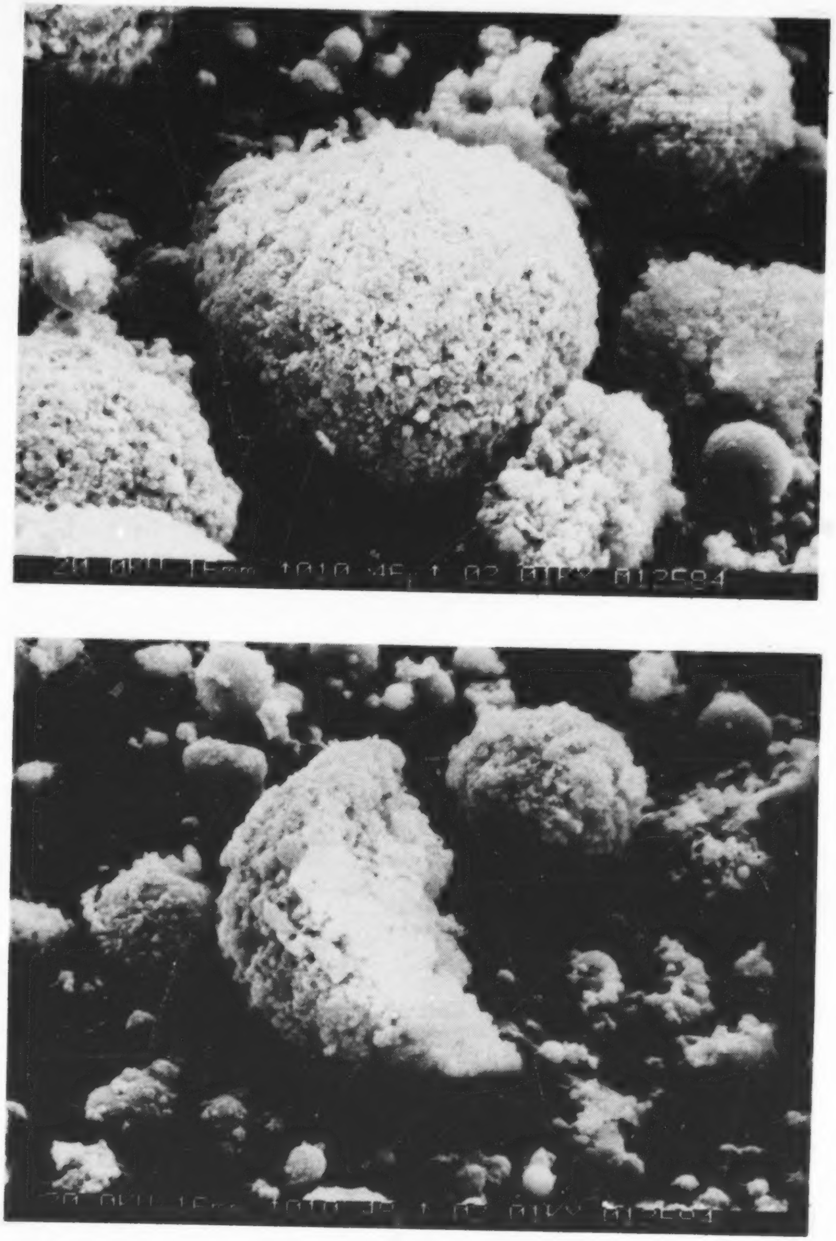


Figure 9-4. Scanning electron micrographs of spray dryer product from the baghouse during high sulfur coal baseline test (90% removal) at Riverside station.

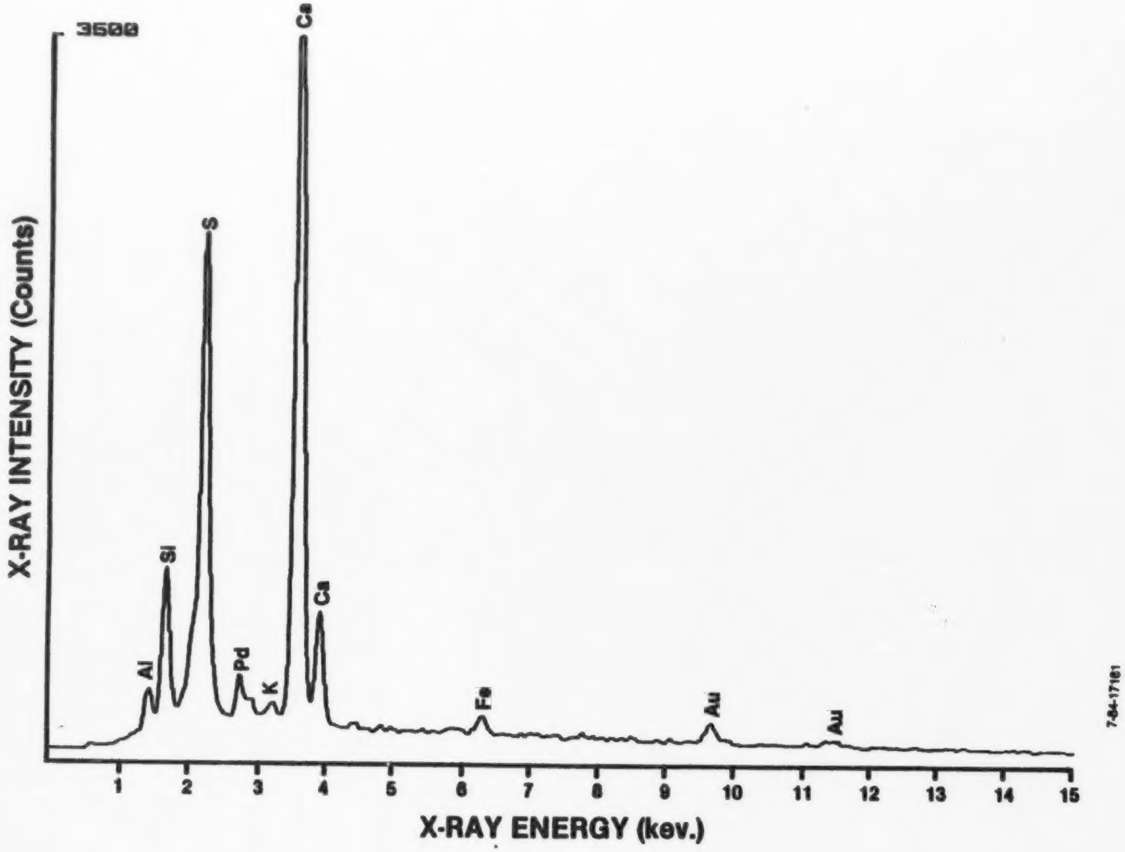


Figure 9-5. Elemental scan of surface of spray dryer product from the baghouse during high sulfur coal baseline test (90% removal) at the Riverside station.

significant number of photomicrographs have not been made for these samples, no conclusions may be made based on these observations.

Figure 9-6 shows two photomicrographs of the waste product sample collected for the high sulfur coal test with chloride addition. As for the baseline high sulfur coal waste product samples depicted in Figures 9-3 and 9-4, the majority of the particles visible in these scans appear to be covered with calcium- and sulfur-containing FGD by-products. Very few predominantly fly ash particles are visible. In fact, a surface elemental scan for a similar particle, as shown in Figure 9-7, indicates the presence of predominantly calcium and sulfur species. Lesser amounts of elements contained in fly ash, such as alumina, silca, and iron, as well as chloride are indicated.

9.4 PHYSICAL PROPERTIES OF COMPACTED AND CURED WASTES

While the previous subsections describe the results of tests and analyses which characterize the raw waste material, this and the following subsection describe the results of tests which provide information about the potential properties of the wastes as landfill material. This subsection describes the results of strength and permeability measurements on moistened, compacted, and cured samples. The following subsection, 9.5, describes the results of determinations of the quality of leachates from these waste samples.

9.4.1 Strength Development

Unconfined compressive strength was measured in samples that were mixed with water, compacted, and cured. Curing consisted of keeping the samples at 100 percent relative humidity and room temperature for a specified period of time. Strength development was measured as a function of both amount of water added and length of time cured.

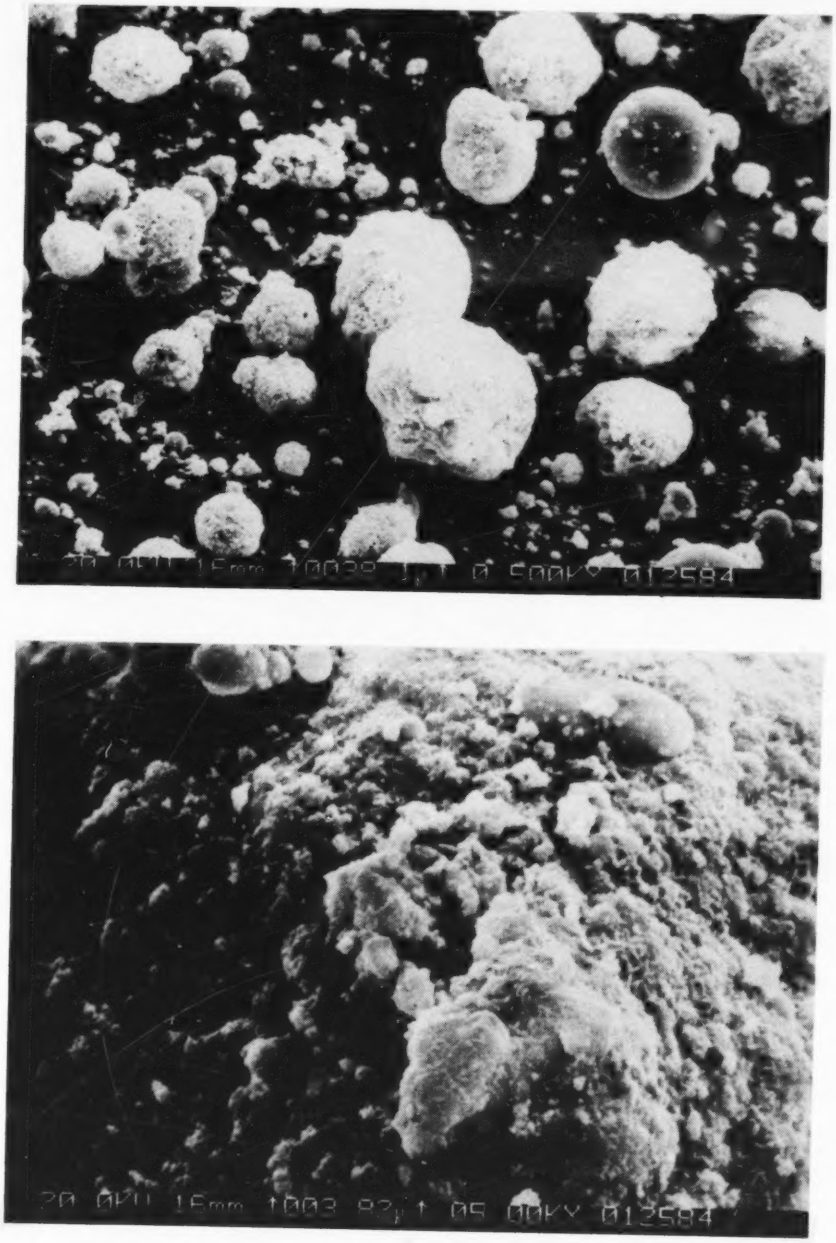

20.0KV 15mm 10039 1.1 0.500KX 012584
20.0KV 15mm 1003 82µ 1 05.00KX 012584

Figure 9-6. Scanning electron micrographs of spray dryer product from the baghouse during high sulfur coal test with $CaCl_2$ addition (90% removal) at Riverside station.

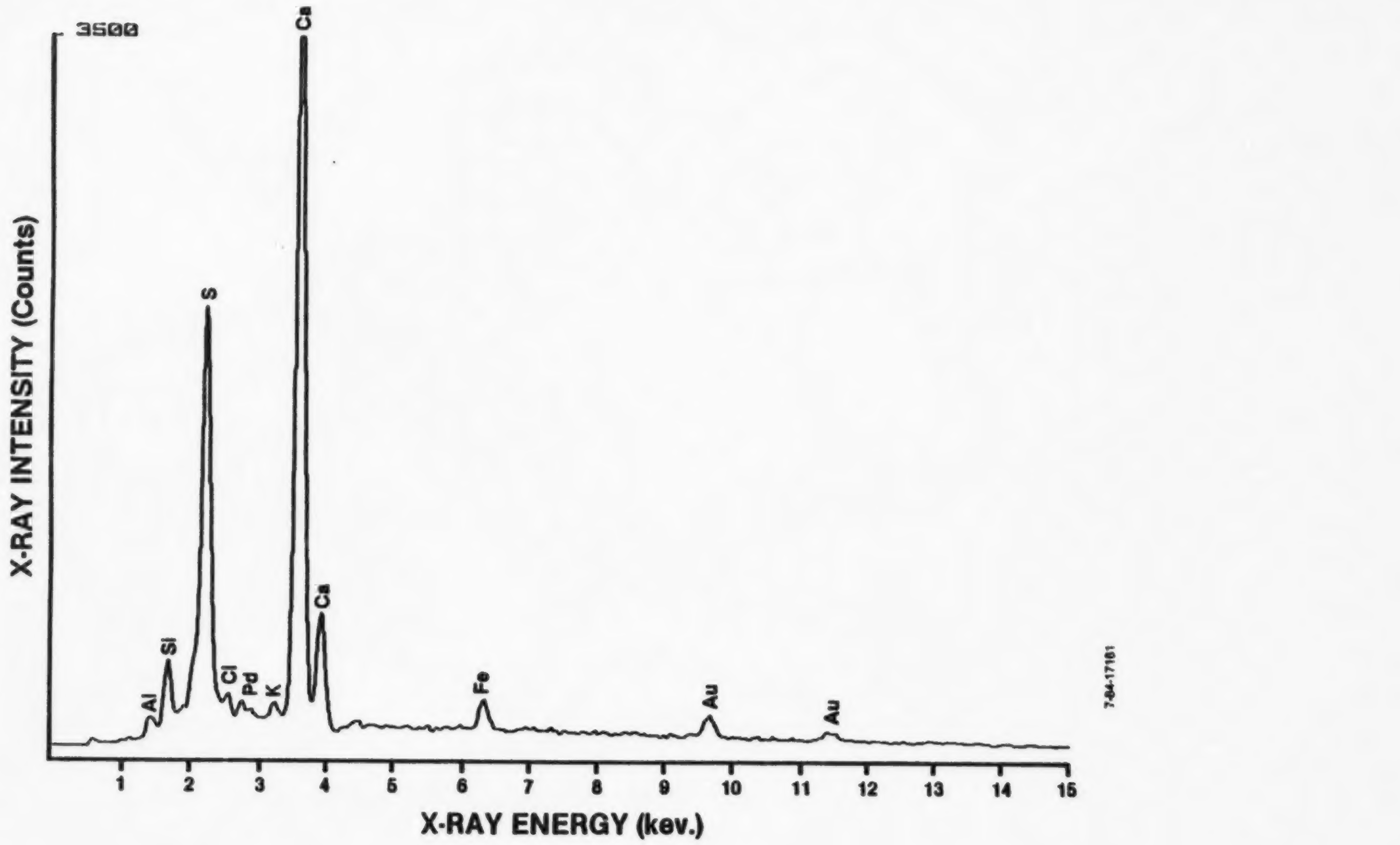


Figure 9-7. Elemental scan of surface of spray dryer product from the baghouse during high sulfur coal chloride addition test (90% removal) at Riverside station.

Samples were prepared with three moisture contents: one with minimum moisture to permit compaction, one with estimated approximate optimum moisture for maximum compacted bulk density and one with an intermediate moisture value. The minimum moisture was determined by adding water in increments until a cohesive mass was formed in the compacting apparatus. To estimate optimum moisture values, known amounts of water were mixed with known amounts of dry solid until the solid particles clung together when only light pressure was applied. If excess moisture appeared on the surface of the solids after application of light pressure, moisture values above optimum were indicated.

The samples were cured for periods of 28 and 56 days. Results are listed in Table 9-6. The values listed are the averages of three individual measurements.

Significant amounts of water had to be added to obtain compactible mixtures. Minimum amounts required were in the range of 20 to 36 pounds of water per 100 pounds of dry waste product. Usually more strength developed as more water was added, up to the optimum moisture value. The optimum moisture value is the highest moisture level tested for each sample in Table 9-6. Two factors can contribute to increased strength with addition of more water. First, particles pack more efficiently as optimum moisture is approached. Second, in some cases hydration reactions can occur similar to those that take place when portland cement sets and hardens.

Average unconfined compressive strengths ranged from 7 psi (0.05 MPa) to 170 psi (1.2 MPa). For comparison purposes, a person walking exerts about 5 psi (0.03 MPa) and a truck with tires inflated to 45 psi (0.3 MPa) will exert 45 psi pressure. Vendors of sludge solidification processes often design their processes to yield treated materials with minimum unconfined compressive strengths in the range of 15 to 30 psi(0.10 to 0.21 MPa).

Waste product from the high sulfur coal without chloride (90 percent removal) and the low sulfur coal (75 percent removal) tests exhibited

TABLE 9-6. UNCONFINED COMPRESSIVE STRENGTH (UCS) FOR RIVERSIDE SPRAY DRYER WASTE PRODUCTS

Sample Description	Percent Moisture		Average 28-Day UCS[c]		Average 56-Day UCS	
	Dry Basis[a]	Wet Basis[b]	(MPa)[d]	(psi)	(MPa)[d]	(psi)
Low Sulfur Coal	20	17	0.3	50	0.4	55
	26	21	0.5	70	0.6	90
	32	24	0.8	120	1.2	170
High Sulfur Coal	36	26	0.2	30	0.3	40
	42	30	0.3	40	0.3	45
	48	32	0.5	70	0.8	110
High Sulfur Coal w/$CaCl_2$	24	19	0.1	20	0.05	7
	32	24	0.2	30	0.15	20
	40	29	0.5	70	0.4	55

[a] Dry Basis = g H_2O/100 g of dry solids

[b] Wet Basis = g H_2O/(100 g of dry solids and H_2O)

[c] Average of three determinations

[d] Megapascals, or 10^6 pascals (1 MPa = 145 psi)

strengths of at least 30 psi (0.21 MPa) at all levels of water addition. These strengths should be sufficient to permit landfill disposal.

The product formed at high flue gas SO_2 levels with chloride added to the feed slurry (90 percent removal) developed only marginal strength at minimum water addition after 28 days. Measurements after curing 56 days showed strength loss relative to the 28-day values at all levels of water addition. These results indicate that high chloride concentrations in the feed solution may lead to long-term strength loss in the waste product. It is not clear whether the apparent strength loss is solely a result of the high chloride content of the wastes or also a result of the low level of excess $Ca(OH)_2$. Excess $Ca(OH)_2$ is thought to contribute to hydration reactions in curing wastes.

Deionized water was used to prepare samples for unconfined compressive strength tests. Dry scrubbing systems are frequently considered for application to western power stations where water availability may be a problem. In many cases it will be desirable to use low quality water (i.e., cooling tower blowdown) to add moisture for compaction. This option should be examined before it is employed because dissolved solids present in these waters may inhibit strength-giving hydration reactions or lead to strength loss from swelling and cracking. This may be one of the reasons for strength losses associated with the high sulfur coal waste sample with chloride addition. Also, leachate quality may be adversely affected by the use of such water. This potential effect is discussed further in subsection 9.5, LEACHATE QUALITY.

9.4.2 Permeability

Permeability is a measure of the rate at which fluids can pass through porous media. Permeabilities usually are described by a permeability coefficient which gives the linear rate of flow of a fluid through the material under unit hydraulic gradient. Samples of spray dryer wastes were mixed with deionized water to the estimated optimum moisture value, compacted, and maintained at high humidity and room temperature for four weeks (28 days) in a manner similar to that described for the strength development tests. However, unlike the strength development tests, lower moisture levels (less than optimum) and longer curing times (56 days) were not tested. Permeability coefficients measured on the cured compacted samples are listed in Table 9-7. Values ranged from 10^{-4} to 10^{-7} cm/sec. Very fine sands; silts; and sand, silt, and clay mixtures have permeability coefficients in the range of 10^{-4} to 10^{-7} cm/sec. Materials with permeabilities in this range are considered to have poor drainage characteristics. Poor drainage characteristics are actually desirable in landfill material. In guidelines identifying and describing available solid waste management practices (1), the Environmental Protection Agency has described low permeability liner materials as those with permeability coefficients equal to or less than 1×10^{-7} cm/sec. Consequently, these cured compacted waste samples had measured permeability coefficients suitable for materials to be landfilled, but not low enough to be considered liner material. Thus liners might be required if this material is to be landfilled.

9.5 WASTE SOLIDS LEACHATE PROPERTIES

An important issue in determining the disposal practices for a given solid waste material is the potential impact of the disposed material on groundwater quality. Extraction of samples of a waste material and analyzing the resulting leachate is one method of evaluating the potential impact of a solid waste material.

Batch extractions provide useful but limited information concerning which species may be leached from a solid material. Limitations exist because batch extractions are carried out with a single leaching solution and at a single liquid-to-solid ratio. If water passes through solids in a landfill, leaching occurs under dynamic conditions. The composition of the leaching solution changes as it passes through the solids and the effective liquid-to-solid ratio also changes.

TABLE 9-7. AVERAGE PERMEABILITY COEFFICIENTS FOR COMPACTED AND CURED RIVERSIDE SPRAY DRYER WASTE PRODUCTS

Sample Description	Permeability Coefficient Mean Value (cm/sec)[a,b]
Low Sulfur	2.6×10^{-5}
High Sulfur	9.6×10^{-7}
High Sulfur with $CaCl_2$	1.0×10^{-4}

[a] Average of 10 determinations

[b] After curing 28 days

The three waste samples from this program were subjected to two batch extractions to establish regulatory classification and to screen for leachable species. Samples were extracted both on an as-received basis and after mixing with water, compacting and curing for four weeks.

The Extraction Procedure (EP) as described in the May 19, 1980, *Federal Register* (2) was one extraction technique used. The other extraction technique used the same type of agitation, the same extraction period, and the same water-to-solids ratio as the EP test. Acetic acid was added during EP extractions as required by the protocol. No acetic acid was added during neutral extractions, and pH values were those that occurred naturally.

9.5.1 Description of Extraction Procedures

The EP test is used to classify solid wastes as toxic (and, therefore, hazardous) under rules and regulations promulgated under the Resource Conservation and Recovery Act of 1976 as amended (RCRA). Residues from coal combustion have been excluded temporarily from possible classification as hazardous. Since the exclusion is temporary, results of the EP test are of interest in assessing long term disposal options. Concentrations of eight trace elements and six pesticides in extracts obtained by this procedure are used to determine whether or not a waste would be classified as hazardous according to the property of EP toxicity. The eight trace elements are those for which maximum contaminant levels (MCLs) in public drinking water supplies have been established. These elements are: arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Concentrations of any of these elements equal to or greater than 100 times the MCL will result in classification as hazardous. No pesticides are expected in spray dryer waste products. The EP test is further described in the May 19, 1980 *Federal Register*(2).

In the EP test, a 100-gram sample of solid is extracted with 16 times its weight of water. Acetic acid (0.5N) is added until the pH of the solution is 5 or until 4 mL of acid have been added for each gram of sample. If less than 400 mL of acid are added during the extraction period of 24 hours, then water is added at the end of the extraction to make a total liquid-to-solid ratio of 20 to 1.

The EP test was developed primarily to test materials that would be disposed of in sites similar to municipal landfills. Leachates from municipal landfill-type disposal sites contain low molecular weight organic acids as the site matures. These acids are produced by chemical and biological action on disposed organic materials. Acetic acid added during the EP test represents organic acids that are to be expected in a disposal site containing wastes from a variety of sources. Also, it may represent inorganic acids found in rainwater.

Neutral Extraction Test

It is anticipated that spray dryer waste products will not be disposed of in municipal landfills but will be placed in separate disposal sites. Organic acids are not expected to be present in these sites. Therefore, acetic acid addition during extraction may not simulate expected disposal conditions for these solids. Extracts obtained at natural pH values may better simulate leaching conditions for these and similar materials.

Consequently, a neutral extraction procedure has been developed. The neutral extraction test is identical to the EP test except no acetic acid is added. The sample is extracted at a total liquid-to-solid ratio of 20 to 1, with the entire liquid portion being comprised of distilled water.

The three samples were extracted by both procedures. The EP test was employed because of current regulatory considerations, and the neutral extraction test was employed because it was felt this procedure may better simulate leaching conditions for spray dryer-based dry FGD waste solids. Also, both cured and uncured samples were extracted. The cured samples were extracted to examine leachability after compaction and exposure to moisture for 28 days. This test was carried out to study the effect of aging on the leaching potential of the compacted wastes. The waste samples were mixed with deionized water to the estimated optimum moisture value for maximum bulk density. Moist samples were compacted in cylindrical molds. Samples were removed from the molds and kept in a humidity chamber at room temperature for four weeks. After curing, intact cylinders were submitted to the Structural Integrity Test, as described in the May 19, 1980 Federal Register. (3), then extracted.

9.5.2 Elemental Concentrations in Extracts

Concentrations of 29 elements were measured in the extracts obtained by the two extraction procedures as applied to both as received and compacted and cured portions of each of the three waste samples. These results are presented in Tables E-1 through E-3 in Appendix E. The results are highlighted below.

Concentrations of RCRA Trace Elements in EP Extracts

Concentrations of the eight RCRA trace elements found in the EP extract of as received and cured samples of each waste product are indicated in Table 9-8. The values listed are the ratios of measured concentrations to the concentrations that cause the solid waste to be classified as toxic according to the EP toxicity test. All values are below unity, indicating that the solids would not be classified as toxic. Since the EP toxicity threshold value for each trace metal is 100 times the MCL for drinking water, each value in Table 9-8 of 0.01 or below indicates that the leachate did not even exceed the MCL for drinking water for that trace metal.

Concentrations of the eight RCRA trace elements in EP extracts varied from below analytical detection limits to nearly 3 percent of the EP toxicity limit. In the low sulfur coal sample, barium concentrations in the EP extract of both the cured and uncured samples were slightly above the MCL for drinking water, but well below the EP toxicity limit. All of the remaining 7 trace element values were well below the MCL for drinking water.

TABLE 9-8. RATIOS OF CONCENTRATIONS TO EP TOXICITY LIMITS IN EP EXTRACTS OF SPRAY DRYER WASTE PRODUCTS FROM TEST FACILITY AT RIVERSIDE STATION[a]

Element	Low Sulfur Coal (75% SO_2 Removal)		High Sulfur Coal (90% SO_2 Removal)		High Sulfur Coal with $CaCl_2$[b] 90% SO_2 Removal)	
	Uncured	Cured[c]	Uncured	Cured[c]	Uncured	Cured[c]
Arsenic	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006
Barium	0.012	0.012	0.016	0.010	0.015	0.009
Cadmium	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Chromium	<0.0002	<0.0001	0.029	0.008	0.026	0.011
Lead	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Mercury	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Selenium	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Silver	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004

[a] Ratios less than 1.0 indicate the EP toxicity limits are not exceeded for that trace element. Ratios less than 0.01 indicate that maximum contaminant levels (MCLs) in public drinking water supplies are not exceeded for that trace element.

[b] $CaCl_2$ added to atomizer feed slurry to achieve approximately 1% Cl in the waste product.

[c] Cured for 28 days with optimum moisture added.

In both high sulfur coal samples, the barium and chromium concentrations in the uncured sample were above the MCLs for drinking water, while the concentrations in the cured samples were at or below the MCL. The remaining 6 trace element concentrations were well below the MCLs for drinking in both the cured and uncured samples.

Comparison of 29 Element Concentrations in Extracts of Uncured Samples

Concentrations in EP extracts and neutral extracts were compared. The comparison is presented in Table 9-9. Generally, concentrations of most elements were similar in the two extracts although large differences occasionally were observed for individual elements. If a neutral extraction procedure was substituted for the EP extraction procedure, these waste products still would be classified as nonhazardous with respect to concentrations of the 8 RCRA trace metals in the extracts.

In the table, increases and decreases are indicated without an estimate of analytical variability. For those elements that exhibit approximately equal numbers of increases and decreases most of the changes probably can be attributed to variability in the extraction procedures and in the analyses. Those elements that exhibited a high proportion of equal concentrations were found in concentrations near or below the analytical detection limits in many of the waste products tested. Elements that exhibited significant trends are discussed in the following paragraph.

The presence of acetic acid is the only difference between the neutral and EP extracts. Acetic acid in the EP extracts lowers the pH relative to the neutral extracts. Acetic acid also may act as a weak complexing agent. It should be noted in comparing the results in Table 9-9 that due to the relatively high level of excess lime in the high sulfur coal baseline sample, the pH of the EP extract is not markedly lower than the neutral extract. For the other two samples, the pH of the EP extract is well below that of the neutral extract.

TABLE 9-9. COMPARISON OF EP EXTRACTS AND NEUTRAL EXTRACTS IN UNCURED SAMPLES OF SOLID WASTE MATERIAL FROM THE RIVERSIDE TEST PROGRAM[a]

	Low Sulfur Coal	High Sulfur Coal	High Sulfur Coal with $CaCl_2$ Addition
Aluminum	+	+	-
Antimony	nc	nc	nc
Arsenic	nc	nc	nc
Barium	nc	-	-
Beryllium	-	+	-
Boron	-	-	-
Cadmium	nc	nc	nc
Calcium	-	-	-
Chromium	+	+	nc
Cobalt	+	+	nc
Copper	+	+	+
Iron	+	nc	-
Lead	nc	nc	nc
Magnesium	-	+	-
Manganese	-	+	-
Mercury	nc	nc	nc
Molybdenum	-	nc	nc
Nickel	-	+	-
Potassium	-	+	-
Selenium	nc	nc	nc
Silicon	-	-	-
Silver	nc	nc	nc
Sodium	-	-	-
Strontium	-	+	-
Thallium	nc	nc	nc
Tin	nc	nc	nc
Titanium	+	+	nc
Vanadium	+	+	-
Zinc	-	+	-
pH Neutral/EP[b]	10.7/6.5	12.4/11.8	11.1/5.5

[a] + = concentration in neutral extract higher than concentration in EP extract.
nc = concentration in two extracts the same.
- = concentration in the neutral extract lower than concentration in EP extract.

[b] pH of neutral extract followed by pH of EP extract.

Concentrations of calcium and magnesium differed most markedly in the two types of extracts. Calcium concentrations were higher in the EP extracts than in the neutral extracts by approximately 300 percent. Magnesium concentrations in the neutral extracts typically were below 2 mg/L; they varied widely in EP extracts from less than 0.05 mg/L to more than 230 mg/L. The reason for these differences cannot be unambiguously identified because solubilities of calcium and magnesium hydroxides and carbonates are markedly influenced by pH. Also, calcium and magnesium ions are complexed by carboxylic acids such as acetic acid. Concentrations of barium, manganese, and strontium tended to be slightly higher in the EP extracts than in the neutral extracts. Again solubility effects of lowered pH and/or complexation cannot be separated.

Comparison of 29 Element Concentrations in Extracts of Cured Samples

Three types of comparisons may be made when reviewing the elemental concentrations from the extracts of the cured samples: determination of the observed effects of aging on the neutral extract concentrations, a similar determination of aging effects on the EP extract concentrations, and a comparison of the concentrations of the elements in the extracts of the cured samples employing the two different extraction procedures.

Lowered concentrations are to be expected in extracts of cured products when samples develop cohesion and are able to survive intact the structural integrity test conducted before the extraction. If the sample remains intact or nearly intact, then a much lower surface area is exposed to the leaching medium. Less benefical effect is expected from curing when waste products do not develop significant structural strength as they are cured.

Extracts of cured waste products, in fact, usually have lower elemental concentrations than extracts of products as they were collected. Decreases, increases, and cases with no change in concentration after curing are indicated in Table 9-10 for neutral extracts and Table 9-11 for EP extracts of

TABLE 9-10. EFFECTS OF CURING ON NEUTRAL EXTRACTS OF RIVERSIDE WASTE SOLIDS[a,b]

	Low Sulfur Coal	High Sulfur Coal	High Sulfur Coal with $CaCl_2$ Addition
Aluminum	-	-	-
Antimony	-	nc	nc
Arsenic	nc	nc	nc
Barium	-	-	-
Beryllium	-	-	nc
Boron	-	-	-
Cadmium	nc	nc	nc
Calcium	-	-	-
Chromium	-	-	-
Cobalt	-	-	nc
Copper	-	-	nc
Iron	-	nc	nc
Lead	nc	nc	nc
Magnesium	nc	-	+
Manganese	-	-	+
Mercury	nc	nc	nc
Molybdenum	-	-	-
Nickel	-	-	nc
Potassium	-	+	+
Selenium	nc	nc	nc
Silicon	-	nc	+
Silver	nc	nc	nc
Sodium	-	+	+
Strontium	-	+	nc
Thallium	nc	nc	nc
Tin	nc	nc	nc
Titanium	-	-	+
Vanadium	-	-	+
Zinc	-	-	-
pH Uncured/Cured[c]	10.7/7.8	12.4/12.3	11.1/9.0

[a] + = concentration in extract of cured waste product higher than concentration in extract of product as collected.

nc = concentration in two extracts the same.

- = concentration in extract of cured waste product lower than concentration in extract of product as collected.

[b] Curing period 28 days.

[c] pH of uncured neutral extract followed by pH of cured neutral extract.

TABLE 9-11. EFFECT OF CURING ON EP EXTRACTS OF RIVERSIDE WASTE SOLIDS[a]

	Low Sulfur Coal	High Sulfur Coal	High Sulfur Coal with $CaCl_2$ Addition
Aluminum	+	+	nc
Antimony	nc	nc	nc
Arsenic	nc	nc	nc
Barium	nc	-	-
Beryllium	+	nc	-
Boron	-	-	-
Cadmium	nc	nc	nc
Calcium	-	nc	-
Chromium	nc	-	-
Cobalt	nc	nc	nc
Copper	+	nc	+
Iron	+	nc	-
Lead	nc	nc	nc
Magnesium	-	+	-
Manganese	-	+	-
Mercury	nc	nc	nc
Molybdenum	-	-	-
Nickel	-	+	-
Potassium	-	+	+
Selenium	nc	nc	+
Silicon	-	+	nc
Silver	nc	nc	nc
Sodium	nc	+	nc
Strontium	-	+	-
Thallium	nc	nc	nc
Tin	nc	nc	nc
Titanium	+	nc	nc
Vanadium	-	nc	-
Zinc	nc	+	-
pH Uncured/Cured[b]	6.5/5.0	11.8/5.0	5.5/5.0

[a] + = concentration in extract of cured waste product higher than concentration in extract of product as collected.

nc = concentration in two extracts the same.

- = concentration in extract of cured waste product lower than concentration in extract of product as collected.

[b] Curing period 28 days.

[c] pH of EP extract of uncured sample followed by pH of EP extract of cured sample.

these three samples. Decreases generally outnumbered increases in both types of extracts. However, in the EP extract of the high sulfur coal baseline run without chloride addition, aluminum, magnesium, manganese, potassium, silicon, sodium, strontium, and zinc were significantly higher in the cured extract. The neutral extract of the high sulfur run with chloride had an equal number of increases and decreases in concentrations for cured and uncured products. In both of these cases, the cured sample crumbled when subjected to the structural integrity test. Consequently, little benefit of curing was expected. Also, for the high sulfur coal baseline sample, the pH of the EP extract of the cured sample was much lower than that of the uncured extract or than that of either neutral extract of the sample. The lowered pH may explain some of the elemental increases in the EP extract not seen in the effects of curing on the neutral extract.

Some of the increases and decreases indicated in Tables 9-10 and 9-11 are rather small in magnitude, of the magnitude that might be expected in duplicate or repeat extractions and analyses of the same sample. However, the overall trend was decidedly toward lower concentrations in extracts of cured products. In many cases, reductions were greater than would be expected from measurement variability.

Elemental concentrations in the EP and neutral extracts of the cured samples also were compared with one another. These comparisons are presented in Table 9-12. Concentrations in the EP extracts were consistently higher than those of the neutral extracts. Only chromium concentrations in the neutral extracts exceeded the EP extracts in all of the waste products.

9.5.3 Anionic Species Concentrations in Neutral Extracts

Concentrations of fluoride, chloride, nitrate, and sulfate were measured in the neutral leachates of both as received and cured portions of the three waste samples. The measured concentrations are listed in Table 9-13. These measurements were made to estimate the leachability of these specific anionic species. Maximum contaminant levels have been established for these

TABLE 9-12. COMPARISON OF EP EXTRACTS AND NEUTRAL EXTRACTS IN CURED SAMPLES OF RIVERSIDE SOLID WASTES[a]

	Low Sulfur Coal	High Sulfur Coal	High Sulfur Coal with $CaCl_2$ Addition
Aluminum	-	-	-
Antimony	nc	nc	nc
Arsenic	nc	nc	nc
Barium	-	-	-
Beryllium	-	nc	-
Boron	-	-	-
Cadmium	nc	nc	nc
Calcium	-	-	-
Chromium	+	+	+
Cobalt	nc	nc	nc
Copper	-	-	nc
Iron	-	-	-
Lead	nc	nc	nc
Magnesium	-	-	-
Manganese	-	+	-
Mercury	nc	nc	nc
Molybdenum	-	nc	nc
Nickel	-	-	nc
Potassium	-	nc	nc
Selenium	nc	nc	nc
Silicon	-	-	-
Silver	nc	nc	nc
Sodium	-	nc	nc
Strontium	-	+	
Thallium	nc	nc	nc
Tin	nc	nc	nc
Titanium	-	nc	+
Vanadium	-	nc	+
Zinc	-	+	-
pH Neutral/EP[b]	7.8/5.0	12.3/5.0	9.0/5.0

[a] + = concentration in neutral extract higher than concentration in EP extract.
nc = concentration in two extracts the same.
- = concentration in the neutral extract lower than concentration in EP extract

[b] pH of neutral extract followed by pH of EP extract.

TABLE 9-13. FLUORIDE, CHLORIDE, SULFATE, AND NITRATE CONCENTRATIONS[a] IN NEUTRAL EXTRACTS OF THE RIVERSIDE SOLID WASTE SAMPLES

Sample Description	Fluoride (mg/L)		Chloride (mg/L)		Sulfate[b] (mg/L)		Nitrate (mg/L)	
	Uncured	Cured	Uncured	Cured	Uncured	Cured	Uncured	Cured
Low Sulfur	<0.1	<0.1	13	12	1,900	310	29	<1
High Sulfur	2.1	1.8	50	39	530	40	28	14
High Sulfur with $CaCl_2$	2.8	<0.1	610	470	710	110	23	10
Maximum Contaminant Level	1.4 to 2.4[c]		250[d]		250[d]		44[e]	

[a] Fluoride concentrations were measured with an ion selective electrode. Chloride, sulfate, and nitrate concentrations were measured using ion chromatography.

[b] Total sulfur species measured as sulfate.

[c] National Interim Primary Drinking Water Regulations [40 CFR Part 141].

[d] National Secondary Drinking Water Regulations [40 CFR Part 143].

[e] National Interim Primary Drinking Water Regulations [40 CFR Partd 141], the MCL is 10 mg/L as nitrogen which corresponds to 44 mg/L as nitrate.

species either in the National Interim Primary Drinking Water Regulations (4) or the National Secondary Drinking Water Regulations (5). As in the case of the RCRA trace elements, the relation between concentrations of these species measured in laboratory extracts and groundwater quality at a proposed disposal site has not been established. Several of the extracts did not meet drinking water quality standards; however, what impact if any, this will have on regulation of disposal practices will have to be determined on a case-by-case basis.

Maximum contaminant levels for flouride and nitrate are listed in the primary drinking water regulations. Concentrations in these two species in groundwater leaving a disposal boundary are regulated in the same way as are concentrations of the eight RCRA trace elements. Maximum contaminant levels for chloride and sulfate are listed in the Secondary Drinking Water Regulations. Extension of Federal rules and regulations to cover application of Maximum Contaminant Levels listed in the National Secondary Drinking Water Regulations for groundwater at the boundary of solid waste disposal sites has been proposed (6), but not finalized as of early 1984.

Fluoride concentrations ranged from <0.1 to 2.8 mg/L in the neutral leachates. Differences in fluoride concentrations may reflect differences in fluoride concentrations in the high sulfur coal and the low sulfur coal. These analyses were not conducted on the original solid samples. For the two samples from the high sulfur coal tests, curing reduced fluoride leachability significantly in the sample where $CaCl_2$ was added, but not in the baseline sample. Nitrate concentrations were consistent in the neutral extracts of all three samples as collected (23 to 29 mg/L), but extract concentrations for cured products ranged from <1 to 14 mg/L. All nitrate concentrations measured were below the MCL for drinking water.

Chloride concentrations ranged from 12 to 610 mg/L. The highest concentrations were associated with the test run in which chloride was added.

Both cured and uncured leachates for this test exceeded the MCL for chloride. None of the three samples saw any substantial reduction in chloride content in the leachate resulting from curing.

Sulfate concentrations ranged from 40 to 1900 mg/L. The leachate sulfate concentrations for all three samples were found to be reduced by 80 to 90 percent by curing. For both the cured and uncured leachates, the sulfate levels were highest for the low sulfur coal sample and lowest for the high sulfur coal baseline sample. The sulfate levels in the leachate appear to correlate with the amount of excess lime in the waste solids based on this observation. All three sulfate concentrations for leachate from the uncured samples exceed the MCL for drinking water, but for the cured samples only that for the leachate from the low sulfur coal test period exceeds the MCL.

It is not possible to relate concentrations of chemical species found in the extracts to requirements that may be imposed by regulatory agencies on disposal practices for these waste products. Part of this ambiguity arises because states regulate disposal practices for nonhazardous wastes and requirements vary from one state to another. More ambiguity arises because the portion of the Federal guidelines for disposal of nonhazardous wastes that deals with the impact of disposal practices on water quality (4) is written in terms of National Pollutant Discharge Elimination System requirements and contamination of groundwater leaving a disposal site rather than in terms of leachate quality per se or in terms of concentrations found in an extract obtained in the laboratory. Concentrations of some of the drinking water elements were above maximum contaminant levels for primary drinking water supplies in laboratory extracts from some of the waste products tested. The relationship between concentrations in laboratory extracts and leachates formed under field conditions has not been established. What impact, if any, concentrations measured in laboratory extracts will have on selection and implementation of disposal practices for spray dryer waste products will have to be established by utilities and state regulatory agenices on a case-by-case basis.

9.5.4 Results of Other Water Quality Measurements on Neutral Extracts

Values of pH, conductivity, and dissolved solids were determined for the neutral extracts from the samples in both as-received and in cured form. The results are listed in Table 9-14. Maximum contaminant levels for pH and dissolved solids are given in the National Secondary Drinking Water Regulations (5) and are also listed in the tables. The same ambiguities described earlier exist between concentrations in laboratory extracts and potential concentrations in groundwater leaving a disposal site. Uncertainties also exist in how regulatory agencies will treat requirements for groundwater protection.

As of early 1984, values of pH and dissolved solids in groundwater leaving the disposal boundary were not covered by Federal rules and regulations. However, proposals had been made to add these species to those covered by Federal regulations.

All pH values measured were alkaline. Values ranged from 10.7 to 12.4 for extracts of samples as collected (uncured) and from 7.8 to 12.3 for extracts of cured samples. In both cases, the pH of the extract appears to correlate with the excess $Ca(OH)_2$ levels in the original sample. Extracts of cured samples had pH values ranging from 0.1 to 2.9 pH units lower than the extract of the corresponding uncured material. However, even for the cured samples the extract from all but the low sulfur coal case, with negligible excess hydroxide ion measured for the original solid sample, exceeded the MCL for pH.

Conductivities ranged from 200 to 600 mS/m (2000 to 6000 μmho/cm) for extracts of samples as collected and from 45 to 400 mS/m (450 to 4000 μmho/cm) for extracts of cured samples. Conductivities of extracts of cured samples were significantly lower than conductivities of extracts of samples as collected. Dissolved solids concentrations also followed the same trend.

TABLE 9-14. OTHER WATER QUALITY PARAMETERS IN NEUTRAL EXTRACTS OF RIVERSIDE SOLID WASTE SAMPLES

Sample Description	pH		Conductivity		Dissolved Solids	
	Uncured[a]	Cured	Uncured[b,c] (ms/m)	Cured (ms/m)	Uncured (mg/L)	Cured (mg/L)
Low Sulfur Coal	10.7	7.8	200	45	2,490	120
High Sulfur Coal	12.4	12.3	600	400	2,430	920
High Sulfur Coal with $CaCl_2$ Addition	11.1	9.0	300	110	2,450	930
NSDWR[d] Maximum Contaminant Level	6.5 to 8.5	6.5 to 8.5	--	--	500	500

---

[a] Uncured products were not subjected to pretreatment before extraction. Cured products were mixed with water, compacted, kept at 100% relative humidity for four weeks, then subjected to the structural integrity test (Federal Register, May 9, 1980) before extraction.

[b] ms/m = millisiemens per meter.

[c] To convert from ms/m to µmho/cm: ms/m x 10 = µmho/cm.

[d] National Secondary Drinking Water Regulations [40 CFR Part 143].

9.6 COMPARISON OF WASTE PRODUCT CHARACTERIZATION WITH RESULTS OF PREVIOUS STUDIES

Prior to participating in this program, the Electric Power Research Institute had funded previous studies of the characteristics of waste products from dry scrubbing systems. Most of the results of these previous studies have been reported in an EPRI publication (7). The results published are for waste product samples collected from a variety of pilot plant studies and from full-scale utility and industrial dry FGD systems. Characterization of waste products from the EPRI Arapahoe spray dryer/baghouse pilot plant are as yet unpublished.

In this subsection, the results of the waste product characterization work for this program are compared with these previous results. The emphasis of these comparisons are on other lime reagent spray dryer-based FGD systems with recycle. However, these previous data are for low to medium sulfur coal firing only. No data from high sulfur coal and recycle operation are available for comparison.

Comparison of the elemental analyses of the waste product samples is not merited, as these values are directly related to site-specifics such as coal ash compositions, coal sulfur levels, and system reagent ratios. However, comparison of anionic species in the waste products provides useful information about carbonate pick-up rates and sulfite oxidation percentages. The carbonate values for these three samples fell in the middle of the range of carbonate levels for baghouse waste solids or mixed spray dryer and baghouse waste solids from recycle systems. The percent oxidation value for the low sulfur coal sample from this program was also quite typical, as the oxidation percentages for the low sulfur coal recycle systems varied from 12 to 55 percent. Most values were between 41 and 55 percent oxidation. No percent oxidation values for high sulfur coal samples are available for comparison. The free moisture levels and chloride concentration values for the two samples from this program without chloride addition were also typical.

The physical properties of the two samples from this program with no chloride addition were typical with respect to optimum moisture level, unconfined compressive strength, and permeability coefficient. However, the sample from the chloride addition test had somewhat atypical physical properties. The unconfined compressive strength values for this sample at optimum moisture were lower than the range previously measured. The 28-day optimum value of 70 psi was somewhat below the range of 100 to 1300 psi from the previous study, while the 56-day value of 55 psi was well below the previous range of 200 to 1900 psi. Also, the permeability coefficient of 1.0×10^{-4} cm/sec was at the low end of the range previously measured. Most samples in the previous study measured permeability coefficients in the 10^{-5} to 10^{-7} cm/sec range.

The concentrations of the eight trace metals present in the EP extracts of these three samples fell within the range of concentrations measured in the previous study. Only the chromium contents of the high sulfur coal EP leachates approached the upper limit of values measured in the previous study. These concentrations, although at the upper limit, did not exceed the range of previously measured values. However, the chloride content of the neutral extract of the high sulfur coal chloride addition test was much higher than any leachate chloride content from the previous study.

In summary, the waste product samples collected during this program appear to have characteristics similar to those from other spray dryer-based FGD systems, particularly for those that also employ product recycle. Even for high sulfur coal operation, for which no data from other systems are readily available, the waste properties appear to be rather similar to those from the predominantly low sulfur systems previously studied. However, the addition of calcium chloride to the atomizer feeds slurry for one high sulfur coal test appears to have adversely affected several waste disposal properties, particularly reducing cured sample unconfined compressive strength, increasing the permeability coefficient, and greatly increasing the chloride content of a neutral extract.

9.7 REFERENCES

1. Federal Register 44(59), 18138-48, March 26, 1979.

2. Federal Register 45(98) 33127, May 19, 1980.

3. "Environmental Protection Agency Regulations on Criteria for Classification of Solid Waste Disposal Facilities and Practices," Environmental Reporter, Federal Regulations, Vol. 3, 161:1281, October 23, 1981.

4. "National Interim Primary Drinking Water Regulations," in Code of Federal Regulations, Title 40, Part 141, (Revised as of July 1, 1981), Washington, DC, Office of the Federal Register, 1981, pp 309-354.

5. "National Secondary Drinking Water Regulations," in Code of Federal Regulations, Title 40, Part 143, (Revised as of July 1, 1981), Washington, DC, Office of the Federal Register, 1981, pp 371-373.

6. Federal Register 44(179), 53465 September 13, 1979.

7. Thompson, C.M., et al, Characteristics of Waste Products From Dry Scrubbing Systems. EPRI CS-2766. Research Project 1870-2. Palo Alto, CA, December, 1982.

APPENDIX A

SAMPLING AND ANALYTICAL PROCEDURES

This appendix contains a description of the sampling and analytical procedures used during this program. The first part of the appendix, A-1, contains a description of sampling and analytical procedures used during the on-site portion of the test program. This portion of the appendix was taken from the Quality Assurance Project Plan for this program. Appendix A-2 is a description of experimental techniques used in the waste characterization study which was described in Section 9.

APPENDIX A-1

SAMPLING AND ANALYTICAL PROCEDURES USED DURING THE ON-SITE TEST PROGRAM

Appendix A-1

SAMPLING AND ANALYTICAL PROCEDURES

Included in this section is a description of the sampling and analytical techniques used to acquire SO_2 removal data, particulate compliance data, and process characterization data.

A.1 SITE DESCRIPTION

Figure A-1 is a sketch of the Riverside Generating Station and Figure A-2 is a schematic diagram of the dry scrubbing system that services Units 6 and 7. The solid, liquid, and slurry sampling locations are also illustrated in Figure A-2. A top view of duct work for Units 6 and 7, including flue gas sampling locations, is illustrated in Figure A-3. Tables A-1 and A-2 contain a brief description of the solid, liquid, slurry, and flue gas sampling locations. The solid, slurry, and liquid sample collection schedule and analysis requirements are summarized in Table A-3.

A.2 CEMS CERTIFICATION AND MONITORING

Continuous emission monitoring systems (CEMS) were used during this program to continuously monitor the SO_2 and O_2 concentrations at the:

- inlet to the spray dryer,
- outlet to the spray dryer, and
- outlet of the baghouse.

To help guarantee the validity of the CEMS data, the CEMS used at the inlet to the spray dryer and the CEMS used at the outlet of the baghouse were certified prior to data collection. Although the same CEMS was used at both the inlet and outlet of the spray dryer, the CEMS was only certified under the inlet conditions. Although the spray dryer outlet location was not certified, relative accuracy tests were conducted throughout the test program to assess the validity of these SO_2 concentration data.

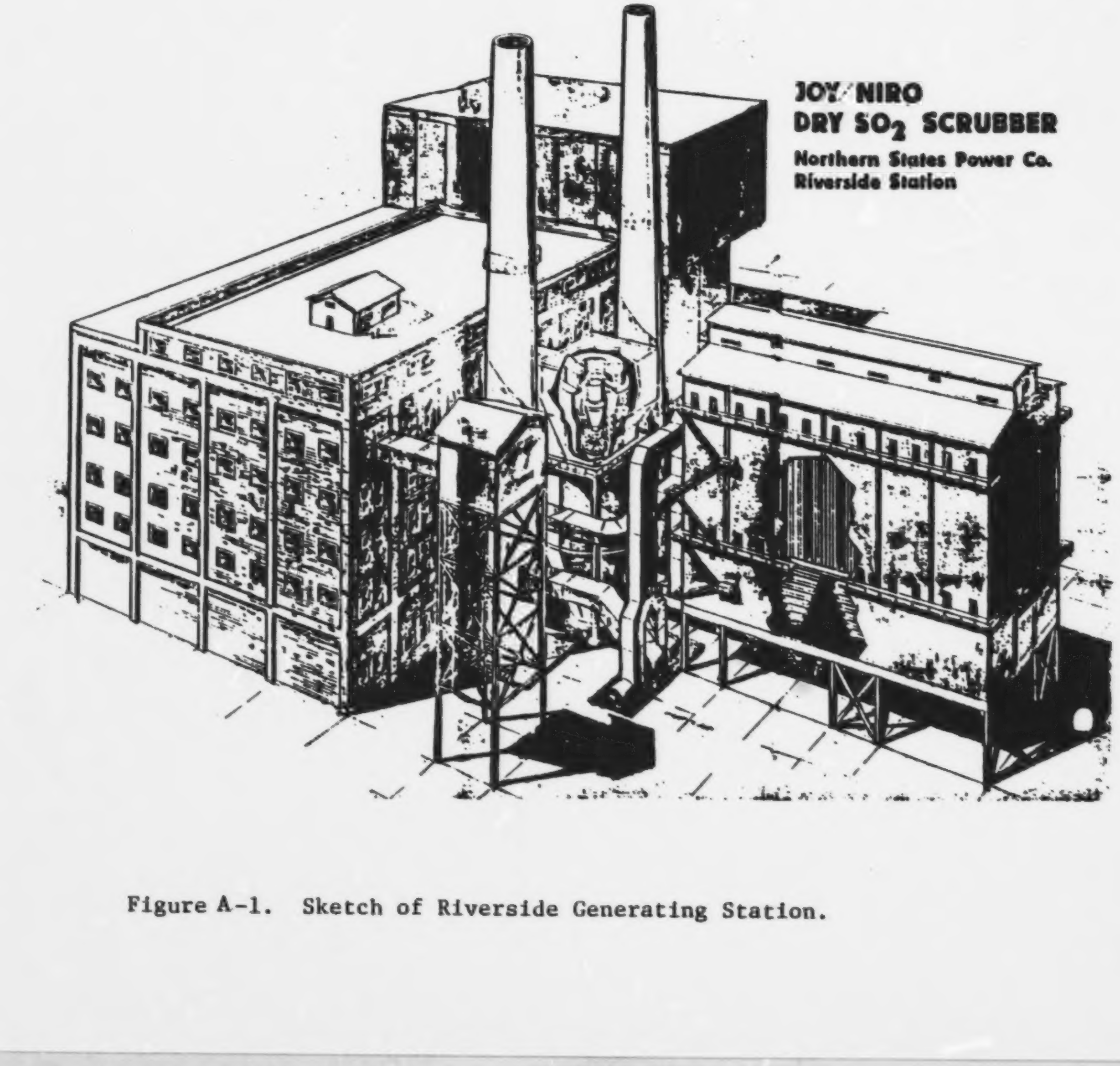

JOY/NIRO
DRY SO_2 SCRUBBER
Northern States Power Co.
Riverside Station

Figure A-1. Sketch of Riverside Generating Station.

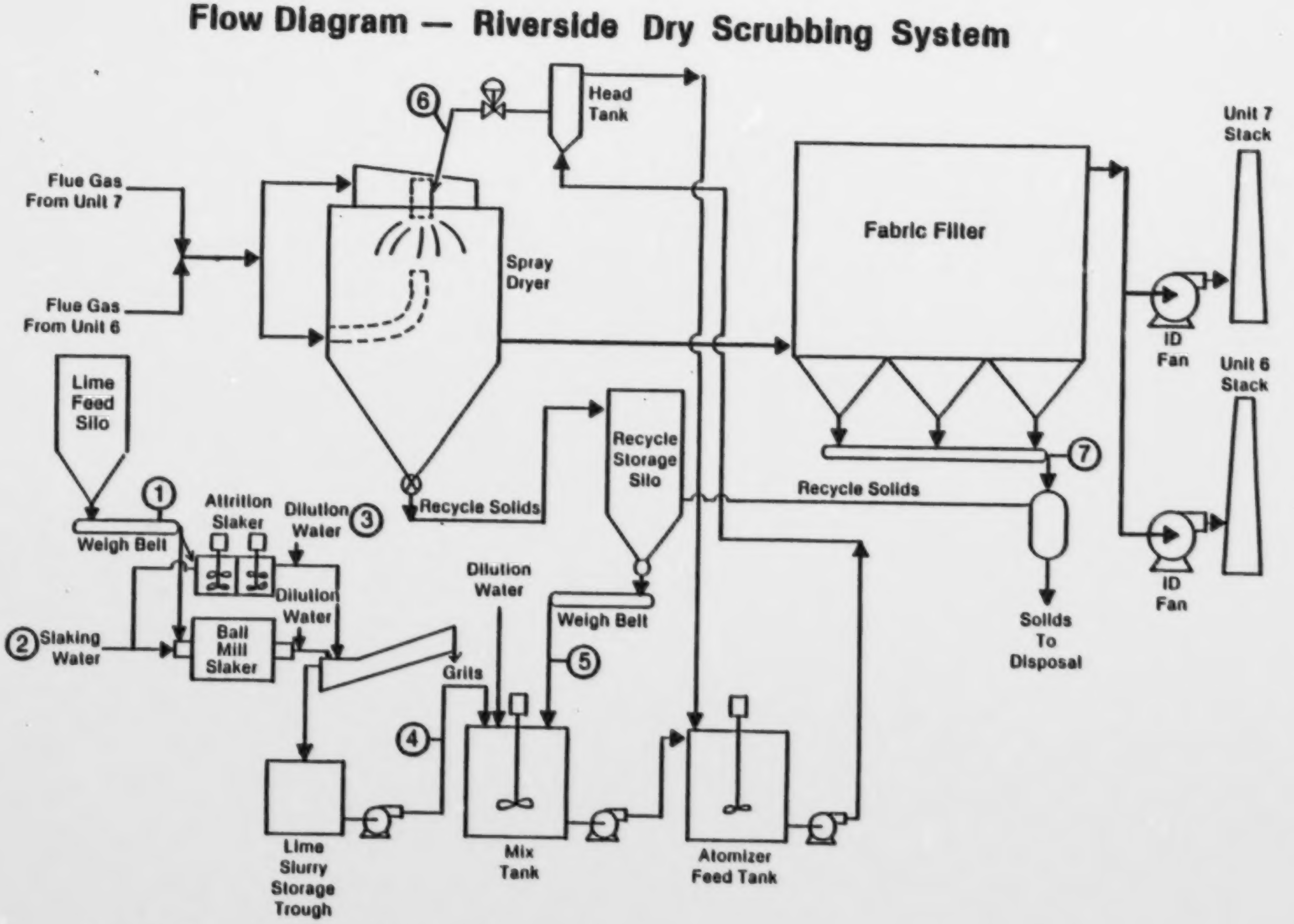

Flow Diagram — Riverside Dry Scrubbing System
Flue Gas From Unit 7
Flue Gas From Unit 6
6
Head Tank
Spray Dryer
Fabric Filter
Unit 7 Stack
ID Fan
Unit 6 Stack
ID Fan
Lime Feed Silo
1
Weigh Belt
Attrition Slaker
Dilution Water
3
2
Slaking Water
Ball Mill Slaker
Dilution Water
Grits
Recycle Solids
Recycle Storage Silo
Recycle Solids
7
Solids To Disposal
Dilution Water
Weigh Belt
5
4
Lime Slurry Storage Trough
Mix Tank
Atomizer Feed Tank

Figure A-2. Solid, liquid, and slurry sample locations on dry scrubbing system at Riverside Generating Station.

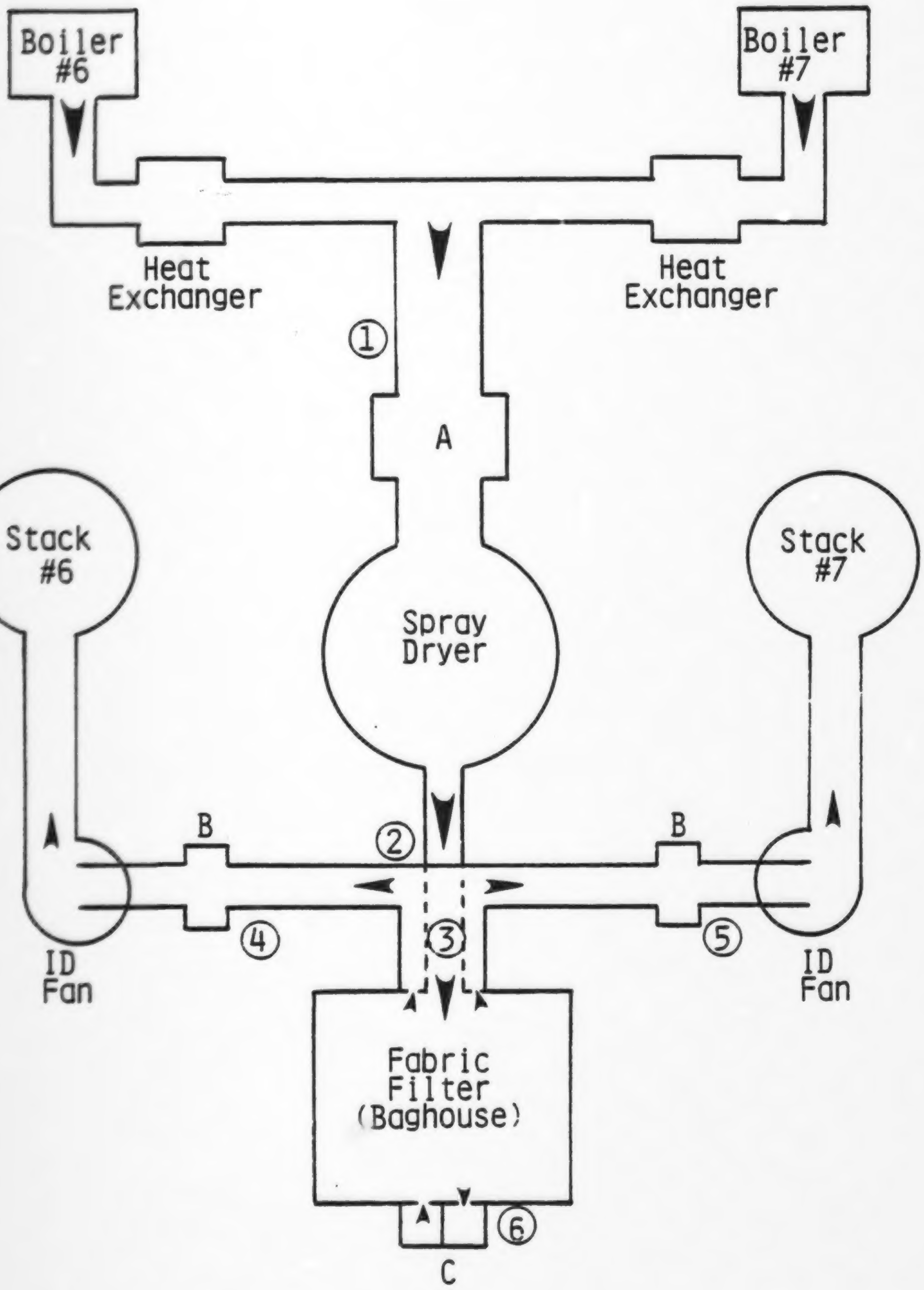

Boiler #6
Boiler #7
Heat Exchanger
Heat Exchanger
①
A
Stack #6
Stack #7
Spray Dryer
B
②
B
④
③
⑤
ID Fan
ID Fan
Fabric Filter (Baghouse)
⑥
C

Figure A-3. Top view of duct work at NSP Riverside Station illustrating flue gas sampling locations.

Note: See Table A-2 for descriptions of circled sample numbers.

TABLE A-1. DESCRIPTION OF THE SOLID, LIQUID, AND SLURRY SAMPLE LOCATIONS ON THE DRY SCRUBBING SYSTEM AT THE RIVERSIDE GENERATING STATION

Sample Location Number[a]	Sample Description
1	Quicklime feed solids
2	Slaker makeup water
3	Process makeup water
4	Lime slurry feed to system
5	Recycle solids
6	Slurry feed to atomizer
7	Fabric filter solids to disposal

[a] Refer to circled sample numbers on Figure A-2.

TABLE A-2. DESCRIPTION OF FLUE GAS SAMPLING LOCATIONS ON THE DRY SCRUBBING SYSTEM AT THE RIVERSIDE GENERATING STATION

Point No.[a]	Location	T(°F)	P(in. H_2O)	Duct Size (inches) deep x across	No. of Ports	Direction of Flow	Sampling Orientation	Depth of Port (in.)	Comments
1	Spray Dryer Inlet	300	-7	144 x 114	5 (vertical, 22" apart)	Horizontal	Horizontal	14	On level 5, several other ports in vicinity, Indoors
2	Baghouse Inlet	140-160	-12	156 x 108	6	Vertical Up	Horizontal	~30	Similar to No.
3	Baghouse Outlet	140-160	-18	~275 x 180	9	Horizontal	Vertical Down	~15	Outside
4	Baghouse Outlet #6	140-160	-20	108 x 108	6	Vertical Down	Horizontal	~30	Indoors, just ahead of ID fan. ~30 feet of run be-location
5	Baghouse Outlet #7	140-160	-20	108 x 108	6	Vertical Down	Horizontal	56	Similar to No.
6	Reverse Gas	140-160	-16	36 x 48	3	Vertical Down	Horizontal	~15	Not much working room; outside

[a] Refers to circled sample number on Figure A-3.

TABLE A-3 SUMMARY OF THE SOLID, SLURRY, AND LIQUID SAMPLING SCHEDULE

Classification	Sample Type	Analytical Requirements[a]	Sampling Frequency
Solid	Lime Feed	Ca^{++}, Mg^{++}, Total S, inerts, reactivity	Once per week
Solid	Fabric Filter Solids	Ca^{++}, Mg^{++}, Total S, $CO_3^=$, $SO_3^=$, inerts, moisture content, composite for waste characterization	One to four per day
Solid	Recycle Material	Ca^{++}, Mg^{++}, Total S, $CO_3^=$, $SO_3^=$, inerts, moisture content	One to four per day
Slurry	Atomizer Feed	Wt.% Solids, pH, Ca^{++}, Mg^{++}, Total S, $CO_3^=$, $SO_3^=$, inerts	One to four per day
Slurry	Lime Slurry	Wt.% Solids, available lime index, reactivity	One to four per day
Liquid	Makeup Water	Total solids, pH, Ca^{++}, Mg^{++}, Total S, $CO_3^=$, temperature	Once per two weeks

[a] Full analyses not completed on all samples.

This section includes a brief description of each CEMS, the certification procedure, and the CEMS monitoring procedure.

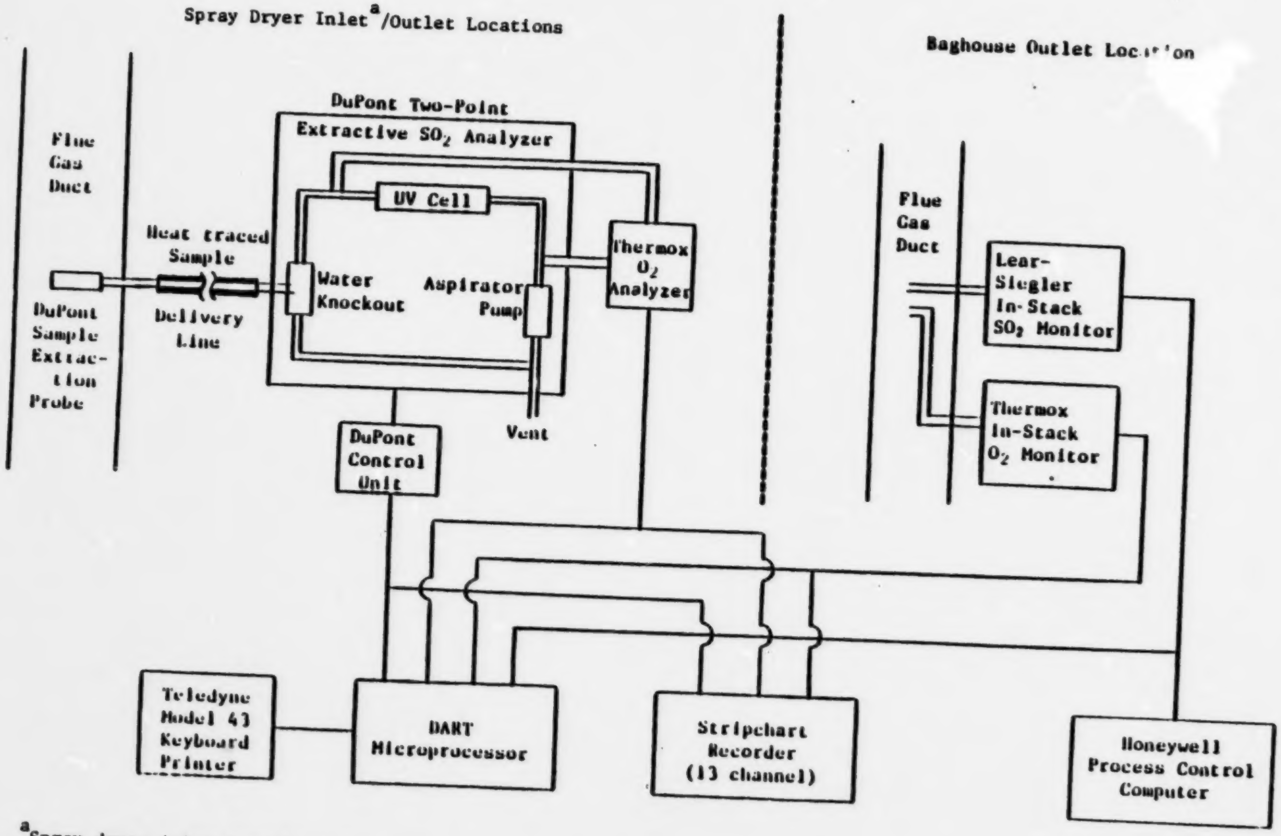
A.2.1 CEMS Description

Figure A-4 includes a schematic diagram of the entire CEMS used on the dry SO_2 scrubber system at Riverside. A DuPont Model 460 dual channel SO_2 analyzer was used to monitor the SO_2 concentration at the spray dryer inlet and outlet. (The data collected at the outlet of the spray dryer were not certified.)

The DuPont SO_2 system consists of individual extractive probes and heat-traced lines for both the inlet and outlet spray dryer sample locations. A water knock-out trap is used to remove any entrained water droplets before the sample gas passes through the heated ultraviolet light (UV) detection cell. The concentration of SO_2 is determined based on the absorption of UV light in the 280 to 313-nanometer (nm) range. An air aspirator is used to pump sample flue gas from the duct through the entire system. An electromechanical timer/programmer was used to cycle automatically between the spray dryer inlet and outlet and auto zero. The signals from the DuPont instrument were fed to a DART microprocessor and simultaneously recorded on a stripchart recorder.

A Lear-Siegler Model SM-810 in-stack short path gas monitor was used to continuously monitor the SO_2 concentration at the outlet of the baghouse. The system is illustrated in Figure A-5 and consists of an in-stack probe and external control module. The probe houses a 10-cm measuring chamber and retroflector. A porous ceramic filter protects the probe internals from particulates while allowing flue gas to permeate through the detection cell.

The control module houses the ultraviolet light source, the optics, the detector, and the necessary electronics. UV light passes through the probe and into the measuring chamber where the light is proportionally absorbed by SO_2. The remaining light is reflected back into the control module where a


Spray Dryer Inlet[a]/Outlet Locations
Baghouse Outlet Location
Flue Gas Duct
DuPont Sample Extraction Probe
Heat traced Sample Delivery Line
DuPont Two-Point Extractive SO₂ Analyzer
UV Cell
Water Knockout
Aspirator Pump
Vent
Thermox O₂ Analyzer
DuPont Control Unit
Flue Gas Duct
Lear-Siegler In-Stack SO₂ Monitor
Thermox In-Stack O₂ Monitor
Teledyne Model 43 Keyboard Printer
DART Microprocessor
Stripchart Recorder (13 channel)
Honeywell Process Control Computer

[a] Spray dryer inlet location only certified.

Figure A-4. Schematic of the CEMS used on the dry SO_2 scrubber system at Riverside.

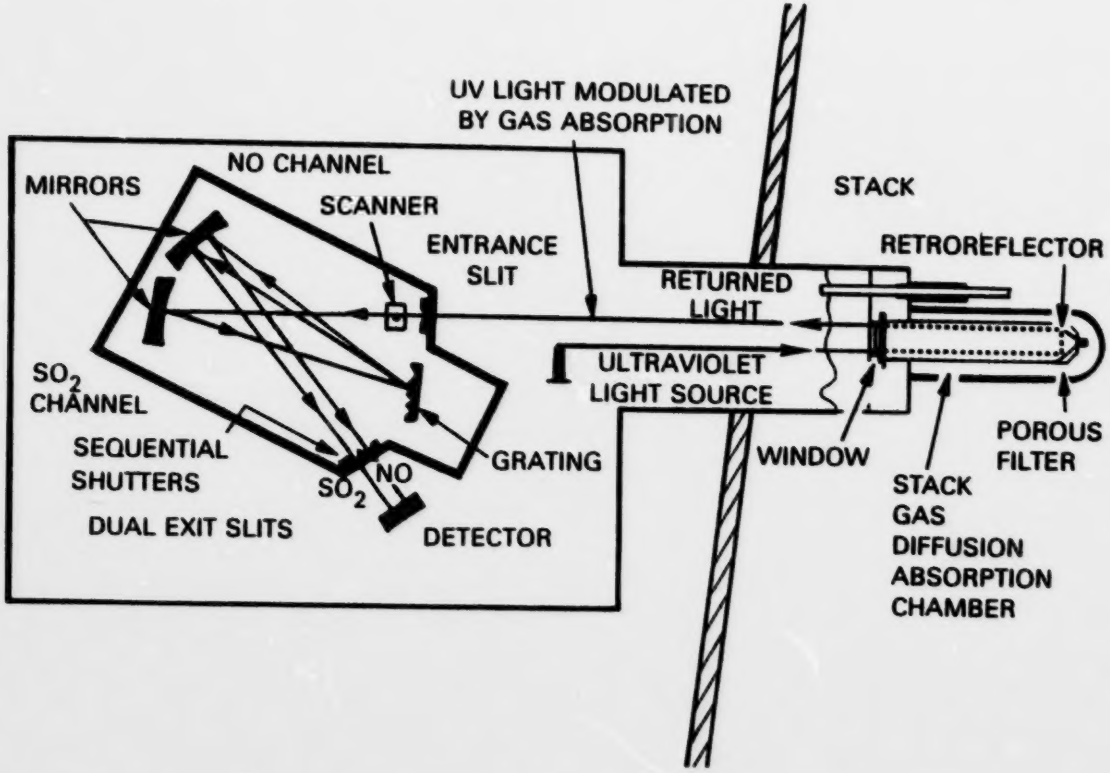

UV LIGHT MODULATED BY GAS ABSORPTION
NO CHANNEL
MIRRORS
SCANNER
ENTRANCE SLIT
STACK
RETROREFLECTOR
RETURNED LIGHT
ULTRAVIOLET LIGHT SOURCE
SO_2 CHANNEL
SEQUENTIAL SHUTTERS
GRATING
WINDOW
POROUS FILTER
NO
SO_2
DUAL EXIT SLITS
DETECTOR
STACK GAS DIFFUSION ABSORPTION CHAMBER

Figure A-5. Schematic of Lear Siegler in-stack monitor.

series of mirrors and slits, a diffraction grating, and detector are used to measure the amount of UV absorption at the 217.8 to 219.2 nm wavelength. The instrument uses a second derivative function to generate an output that is proportional to both gas concentration and the optical pathlength. The signals from the Lear-Siegler monitor were fed to a DART microprocessor and simultaneously to a Honeywell process computer in the control room.

Current regulations (1) require that the SO_2 concentration be reported in units of mass of SO_2 per energy produced (e.g., lbs/10^6 Btu). To accomplish this, the excess oxygen (or CO_2) must be monitored in order to "back out" the excess dilution air. During this program, Thermox O_2 analyzers were used to continuously monitor the O_2 at the inlet and outlet of the spray dryer and the outlet of the baghouse.

One Thermox O_2 analyzer was plumbed into the existing DuPont sample extraction system (refer to Figure A-4) and monitored the O_2 concentration at the inlet and outlet of the spray dryer. A second Thermox O_2 analyzer was installed near the Lear-Siegler SO_2 analyzer in order to monitor the O_2 concentration in the outlet of the baghouse.

The Thermox O_2 analyzer utilizes an electrochemical cell to produce a linearized voltage signal that is proportional to the ratio of the oxygen concentration of the reference gas (usually ambient air) and the oxygen concentration of the sample. The signals from the two Thermox O_2 analyzers were fed to a DART microprocessor and simultaneously recorded.

A.2.2 Certification Procedure

The certification procedure for an SO_2 CEMS specified in the regulations (1) consists of the following major components:

- CEMS installation and measurement location selection,
- performance specifications,
- calibration drift tests,

- CEMS relative accuracy tests, and
- calculations.

Only the site-specific aspects of each of the above components will be discussed here.

A.2.2.1 CEMS Installation and Measurement Location Selection

Spray Dryer Inlet. Flue gas from boilers 6 and 7 are combined just upstream of the spray dryer. Both boilers burn the same coal, but air leakage across the air heater is not the same for both boilers. SO_2 and O_2 stratification is frequently encountered in the horizontal duct work just upstream of the spray dryer. The stratification does not affect the overall results since the emission rate units are adjusted for excess air. The DuPont probe was installed within the inner 10 percent of the cross-sectional area of the duct.

Baghouse Outlet. A Lear-Siegler (LSI) Model SM-810 instack SO_2 monitor was situated in the side of the single duct (Figure A-3, Sampling Location 3) exiting the baghouse. This monitor had been in operation for several years and SO_2 data generated by the monitor have been substantiated by material balances.

Flue gas samples for the baghouse outlet were collected at the two vertical ducts (refer to Figure A-3, Sampling Locations 4 and 5) that diverge from the single duct exiting the baghouse. Both outlet ducts consist of a series of six horizontally oriented ports that are well suited for sampling and are easily accessible. Relative accuracy tests were conducted simultaneously on both the outlet ducts. All baghouse outlet flue gas sampling was conducted on these two vertical ducts.

A.2.2.2 CEMS Relative Accuracy Tests

The CEMS located at the spray dryer inlet and at the baghouse outlet were certified by conducting a series of 9 to 12 relative accuracy tests at each location. The relative accuracy tests were performed using the methods specified in the regulations (1). The SO_2 and H_2O flue gas concentrations were determined using a combined EPA Method 6 (refer to Section A.3.3) and EPA Method 4 (refer to Section A.4.1) sampling train. O_2 flue gas concentrations were determined simultaneously with the SO_2 and H_2O using the integrated bag sampling technique described in EPA Method 3 (refer to Section A.3.4).

Relative accuracy testing at the inlet to the spray dryer was conducted using one of the existing six vertically oriented ports in the inlet duct (refer to Figure A-3, Sampling Location 1). A minimum of three points were traversed for each flue gas sample.

Relative accuracy testing at the outlet of the baghouse was conducted by simultaneously sampling a single port on each of the two vertical ducts (refer to Figure A-3, Sampling Locations 4 and 5). A minimum of three points were traversed for each flue gas sample. The results of the two baghouse outlet flue gas samples collected simultaneously were averaged to determine the baghouse outlet concentration.

A.2.3 CEMS Monitoring

To help ensure data quality after certification, a span and zero check were performed once each day of testing. A QC gas was also used to verify the stability of each CEMS in the approximate concentration range of the flue gas being monitored.

Before testing was initiated using the high sulfur Illinois coal, the DuPont SO_2 analyzer was respanned using an SO_2 span gas of 3000 ppm. A series of relative accuracy tests were performed at the spray dryer inlet and baghouse outlet to establish the accuracy of the two CEMS under high sulfur coal conditions.

A.3 FLUE GAS SAMPLING AND ANALYSIS PROCEDURES

A summary of the flue gas sampling and analysis procedures used during this program are summarized in Table A-4. Whenever possible, referenced source sampling/analysis methods were used. If a reference method does not exist, a detailed description of the methodology is provided.

TABLE A-4. SUMMARY OF FLUE GAS SAMPLING AND ANALYSIS PROCEDURES

Parameter	Sampling Methodology
Gas Phase Composition	
Moisture	EPA Method 4
Molecular Weight (N_2, O_2, CO_2)	EPA Method 3
SO_2	EPA Method 6
Volumetric Gas Flow Rate	EPA Method 2
Grainloading	EPA Method 17
SO_3/H_2SO_4	Controlled Condensation

A.3.1 Flue Gas Moisture Determination

The moisture content of the flue gas was determined using a modified version of the methodology described in EPA Method 4 (3). Based on this method, a known volume of particulate-free gas is pulled through a chilled impinger train. The quantity of condensed water is determined gravimetrically and then related to the volume of gas sampled to determine the moisture content.

During this project, the moisture content of the flue gas was determined simultaneously during the operation of the particulate, SO_2, and H_2SO_4/SO_3 sampling trains. The impingers used with these sampling trains were weighed before and after sampling. The mass increase (H_2O) was then related to the volume of gas sampled to calculate the moisture content.

A.3.2 Flue Gas Molecular Weight Determination

During testing, the integrated sampling technique described in EPA Method 3 (4) was used to obtain a composite flue gas sample for O_2 and CO_2 analysis. A small diaphragm pump and a stainless steel probe was used to extract the flue gas sample which was collected in a Mylar® bag. Moisture was removed by an air-cooled condenser so that the measured O_2 and CO_2 values are on a dry basis. The composition of the composite gas sample was subsequently determined using an Orsat apparatus. The balance of the dry gas mixture was assumed to be N_2. If more than 6 passes were required to obtain a constant ($\leq 0.3\%$ difference, absolute) reading for either O_2 or CO_2, the appropriate absorbing solution was replaced. The SO_2 concentrations were well below the 5000 ppm level at which correction of the CO_2 concentration is required.

A.3.3 Flue Gas SO_2 Determinations

During this program, the SO_2 content of the flue gas was determined using two different sampling systems. Both sampling systems used were modifications of the methodology specified in EPA Method 6 (5). Based on EPA Method 6, a gas sample is extracted from the stack and the sulfuric acid mist (including sulfur trioxide) and the sulfur dioxide are separated.

During CEMS certification, the sampling train illustrated in Figure A-6 was used to collect SO_2 samples. A heat traced stainless steel probe was used to extract a gas sample from the stack. A plug of glass wool was placed in the probe to remove particulate matter from the flue gas. Gas exiting the probe entered a series of five impingers. The first impinger contained 250 ml of 80% IPA for SO_3 removal. A plug of glass wool was placed in the top of the first impinger to prevent H_2O_2 for SO_2 removal. The fourth impinger was dry and the fifth impinger contained silica gel for final water removal. A pump and dry gas meter were used to control and monitor the flow rate of the sample gas. The gas flow rate was maintained at 0.4 to 0.5 cfm during a sampling period of about 21 minutes.

SO_2 gas samples were also collected during EPA Method 17 (7) grain-loading determinations. The overall procedure is very similar to the above-mentioned procedure except for the gas sample flow rate and the total gas volume collected. Sampling during EPA Method 17 was conducted isokinetically at the nozzle and the total gas volume collected was adjusted to provide a satisfactory sample for weighing.

After sampling was completed, the two peroxide impingers were analyzed for SO_2 (as $SO_4^=$) by means of the barium-thorin titration procedure outlined in EPA Method 6. A Dionex ion chromatograph (Section A.4.2.7) was also used to determine the $SO_4^=$ content of several peroxide impinger samples. The Dionex results were compared to the barium-thorin titration results to help ensure data quality.

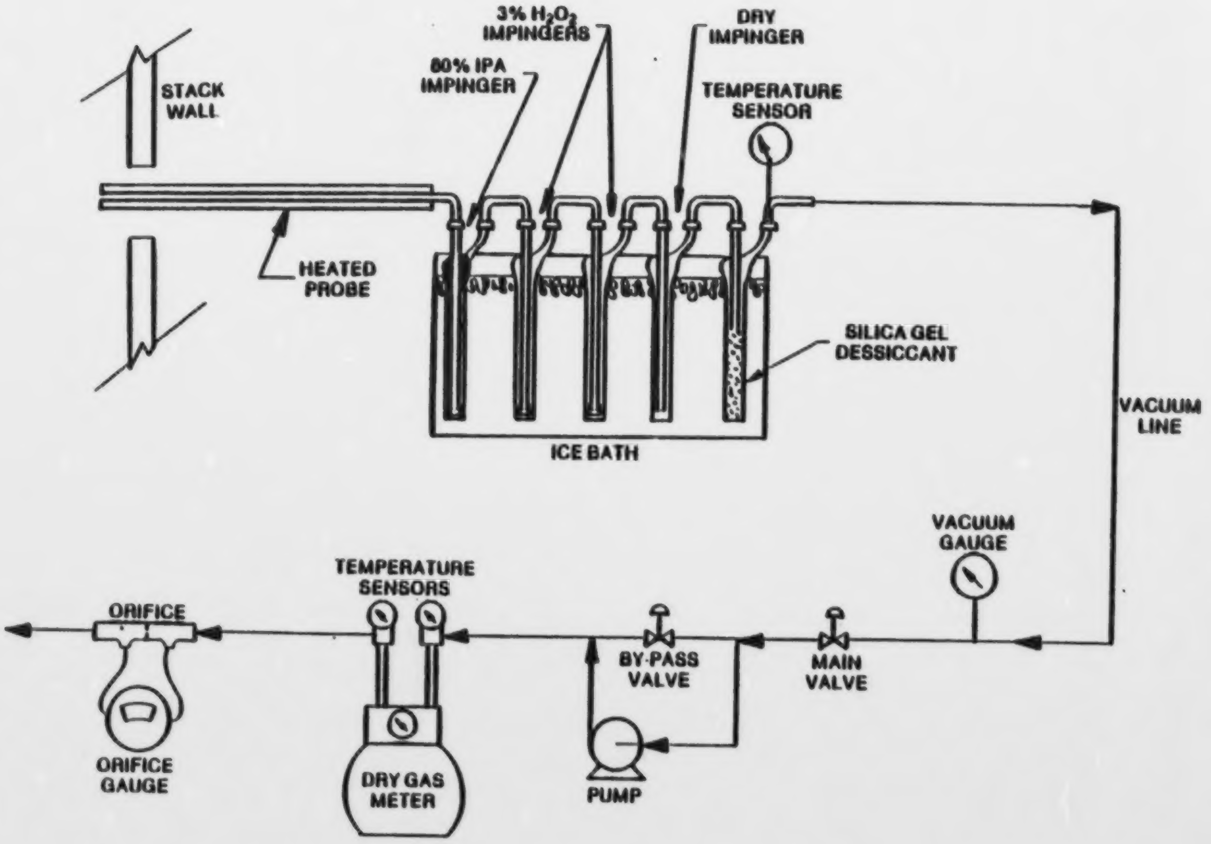

STACK WALL
HEATED PROBE
80% IPA IMPINGER
3% H_2O_2 IMPINGERS
DRY IMPINGER
TEMPERATURE SENSOR
SILICA GEL DESSICCANT
ICE BATH
VACUUM LINE
VACUUM GAUGE
MAIN VALVE
BY-PASS VALVE
PUMP
TEMPERATURE SENSORS
DRY GAS METER
ORIFICE
ORIFICE GAUGE

Figure A-6. EPA Method 6 SO_2 sampling train.

A.3.4 Volumetric Gas Flow Rate Determination

The volumetric gas flow rate was determined during this program using procedures described in EPA Method 2 (3). Based on this method, the volumetric gas flow rate is determined from the product of the measured cross-sectional area of the duct and the average velocity of the flue gas.

The average flue gas velocity is calculated from the average pitot pressure drop (ΔP), the average flue gas temperature, wet molecular weight, and the absolute static pressure in the duct. ΔP and temperature profile data were obtained by traversing the duct. The number of sampling points required to measure the average gas velocity was determined using the procedures outlined in EPA Method 1 (2). The number of sampling points and their distance from the duct wall is a function of the proximity of the sampling location to its nearest upstream and downstream flow disturbance.

ΔP and temperature profile data were measured at each of the sampling points using an S-type pitot tube and K-type thermocouple. A Magnehelic® gauge of the proper range was used to measure the pressure drop (ΔP) across the S-type pitot. A mercury barometer was used to obtain barometric pressure readings at least twice a day. The static gas pressure at the scrubber inlet and outlet was measured by disconnecting one side of the S-type pitot and then rotating the pitot so that its tube opening plane was perpendicular to the gas flow. A Magnehelic® gauge was attached to the S-type pitot to measure the static pressure within the duct.

A.3.5 Particulate Grainloading Determinations

A modified version of the sampling train specified in EPA Method 17 (7) was used to determine the total particulate grainloading during this program. Figure A-7 graphically illustrates the EPA Method 17 sampling train.

Based on this technique, a sample of particulate-laden flue gas is collected isokinetically using a stainless steel gooseneck nozzle. The

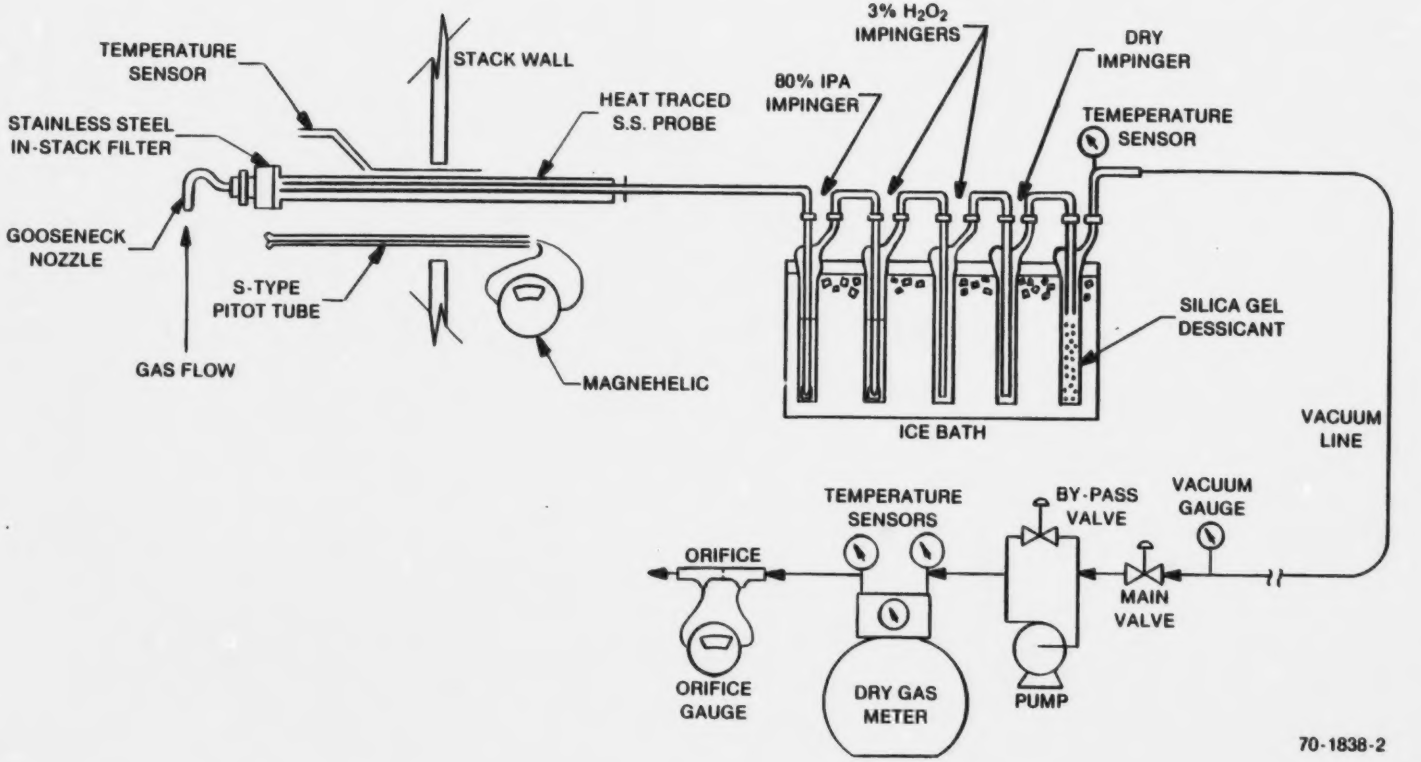

TEMPERATURE SENSOR
STACK WALL
HEAT TRACED S.S. PROBE
STAINLESS STEEL IN-STACK FILTER
GOOSENECK NOZZLE
S-TYPE PITOT TUBE
GAS FLOW
MAGNEHELIC
80% IPA IMPINGER
3% H_2O_2 IMPINGERS
DRY IMPINGER
TEMEPERATURE SENSOR
SILICA GEL DESSICANT
ICE BATH
VACUUM LINE
VACUUM GAUGE
MAIN VALVE
BY-PASS VALVE
PUMP
TEMPERATURE SENSORS
DRY GAS METER
ORIFICE
ORIFICE GAUGE
70-1838-2

Figure A-7. EPA-17 in-stack total particulate sampling train.

particulate is removed from the gas stream by means of a Gelman Spectrograde filter that is housed in a 42-mm stainless steel filter holder. An Andersen preimpactor was used at the spray dryer inlet to remove large particles (>10 µm) from the sample gas before admission to the Gelman filter. Use of the Andersen preimpactor at the inlet increases the total mass of particulate that can be collected before the filter must be changed.

A heat-traced stainless steel probe is used to transfer the filtered gas out of the duct to the impingers. A chilled impinger train is used to quantitatively remove SO_2 and H_2O from the flue gas. A pump and dry gas meter were used to control and monitor the gas flow rate. A minimum sampling period of one hour was used to collect the particulate samples.

After sampling was completed, the nozzle, Andersen preimpactor (where applicable), and any interconnecting pieces prior to the filter were washed with acetone and deionized water to remove any particulate matter present. The resulting wash was evaporated and the mass of particulate remaining was determined. The glass fiber filter was removed from the filter holder, desiccated, and then weighed to determine the mass of particulate present on the filter. The total mass of particulate present on the filter and in the probe was was then related to the total volume of gas sampled to determine the particulate grainloading.

The impingers used during particulate sampling were weighed before and after sampling in order to determine the moisture content of the flue gas. The contents of the perioxide impingers were saved so analyses could be performed to determine the SO_2 concentration in the flue gas.

A.3.6 Flue Gas SO_3/H_2OSO_4 Determination

A controlled condensation sampling technique was used in the separation and quantitative collection of SO_3/H_2SO_4 and SO_2 present in the flue gas. The sampling train (Figure A-8) consists of the following basic components:

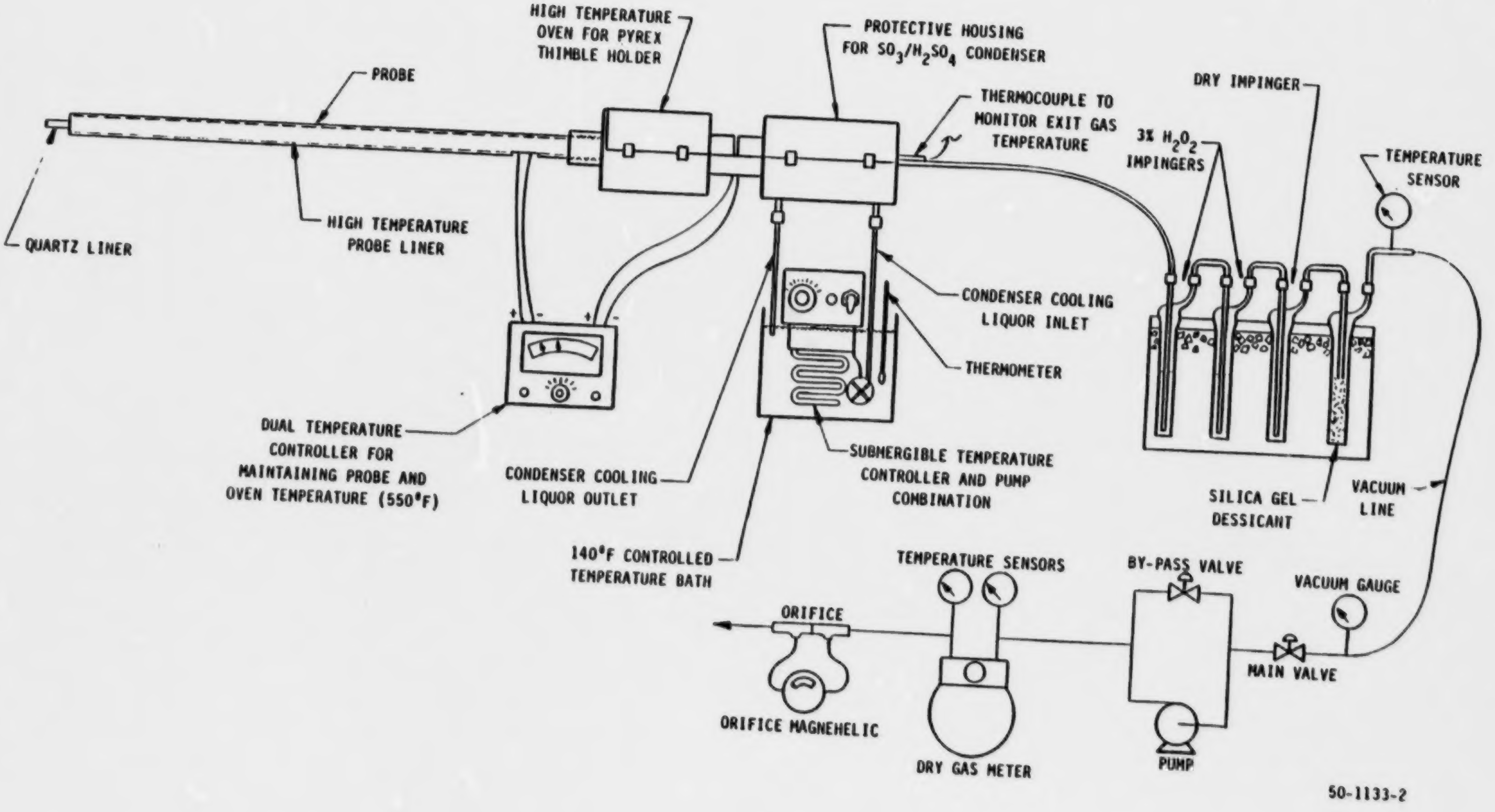

HIGH TEMPERATURE OVEN FOR PYREX THIMBLE HOLDER
PROTECTIVE HOUSING FOR SO_3/H_2SO_4 CONDENSER
PROBE
THERMOCOUPLE TO MONITOR EXIT GAS TEMPERATURE
DRY IMPINGER
3% H_2O_2 IMPINGERS
TEMPERATURE SENSOR
QUARTZ LINER
HIGH TEMPERATURE PROBE LINER
CONDENSER COOLING LIQUOR INLET
THERMOMETER
DUAL TEMPERATURE CONTROLLER FOR MAINTAINING PROBE AND OVEN TEMPERATURE (550°F)
CONDENSER COOLING LIQUOR OUTLET
SUBMERGIBLE TEMPERATURE CONTROLLER AND PUMP COMBINATION
SILICA GEL DESSICANT
VACUUM LINE
140°F CONTROLLED TEMPERATURE BATH
TEMPERATURE SENSORS
BY-PASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
ORIFICE MAGNEHELIC
DRY GAS METER
PUMP
50-1133-2

Figure A-8. SO_2-SO_3/H_2SO_4 sampling train.

- a high temperature (550°F) quartz-lined probe,
- a high temperature (550°F) quartz filter holder for particulate removal,
- a temperature controlled (140°F) condenser for collection of SO_3/H_2SO_4,
- an impinger train for SO_2 collection and moisture removal, and
- a pump and dry gas meter for controlling and monitoring sample flow.

This system design was based on previous work sponsored by the EPA (9,10).

A special high temperature (900°F maximum) probe was fabricated for use with this equipment. A thermocouple mounted against the probe liner was used with a temperature controller to monitor and maintain the desired probe temperatures. The probe was of sufficient length to allow traversing of the inlet and outlet ducts.

Attached directly to the back of the probe is a specially fabricated cylindrical high temperature (650-700°F maximum) controlled oven. The oven is designed to securely house a Pyrex thimble holder and maintain the thimble at 500°F. The thimble holder (Figure A-9) is designed to hold a 19 x 19 mm glass fiber thimble. Flue gas exiting the probe's quartz liner immediately enters the thimble holder where entrained particles are removed from the gas stream when the gas passes through the thimble.

A thermocouple mounted in the thermocouple well directly behind the thimble is used with a temperature controller to maintain the desired temperature. The probe and filter holder oven are maintained between 550°F and 600°F to keep the flue gas well above the dew point of SO_3/H_2SO_4 (450°F).

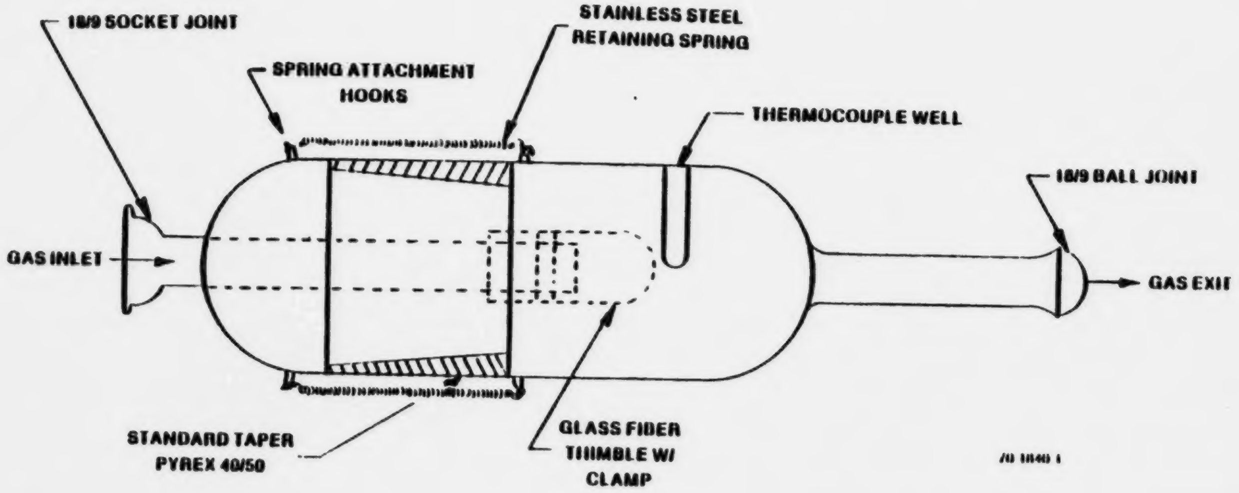

18/9 SOCKET JOINT
SPRING ATTACHMENT HOOKS
STAINLESS STEEL RETAINING SPRING
THERMOCOUPLE WELL
18/9 BALL JOINT
GAS INLET
GAS EXIT
STANDARD TAPER PYREX 40/50
GLASS FIBER THIMBLE W/ CLAMP

Figure A-9. Pyrex thimble holder.

SO_2 and SO_3/H_2SO_4 exiting the thimble holder enter a modified Graham condenser that is housed in an insulated cylindrical enclosure. SO_3/H_2SO_4 is removed from the gas stream by condensation in the condenser. Condenser temperature is maintained at 140-160°F. A high capacity submergible pump is used to recirculate condenser liquor through the system. A submergible heater maintains the condenser liquor temperature. SO_2 is not removed from the gas stream in the condenser provided that the gas temperature is maintained above the dew point of water present in the flue gas.

A glass wool plug condenser (Figure A-10) is used to collect the condensed SO_3/H_2SO_4 sample. A plug of precleaned glass wool is inserted into the back section of the condenser to remove any entrained H_2SO_4 mist. A second condenser design is available for use. But, because it uses a glass frit instead of the glass wool plug there is a considerable increase in the system pressure drop. Radian's experience with the two condensers as well as previous work (1) has shown that the glass wool condenser performs as well or better than the fritted condenser.

SO_2 and moisture present in the gas exiting the condenser are collected in a series of impingers. The first two impingers are of the Greenburg-Smith design and contain 250 mL of three percent H_2O_2 for SO_2 sorption. The third and fourth impingers are both of the modified Greenburg-Smith design. The third impinger is dry and the fourth contains silica gel for final moisture removal. Gas exiting the final impinger then passes through a leakless pump that controls the sample acquisition rate. The total volume of gas samples is measured by a dry gas meter located directly downstream of the pump. All sampling and impinger data are recorded on the source sampling data sheets.

During sample collection, a proportional sampling technique was used to collect a representative gas sample. This technique collects a volume of gas at each sampling point that is proportional to the total gas flow rate at that point. After sampling was completed, the filter holder and condenser were removed from the system and taken back to the on-site laboratory.

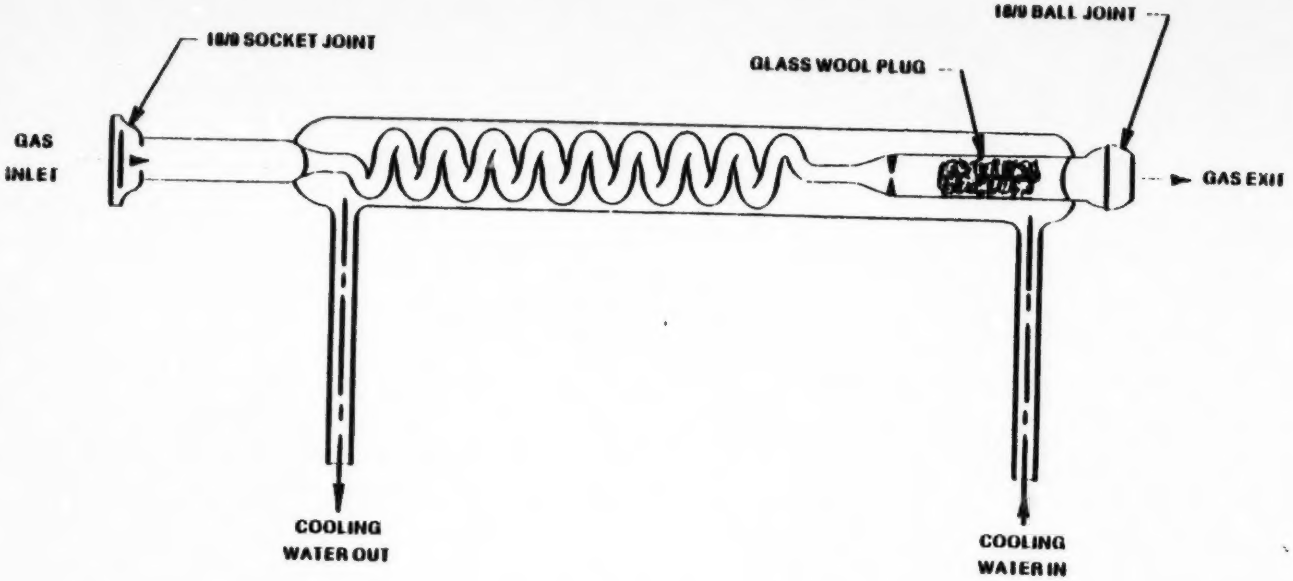

18/9 SOCKET JOINT
GAS
INLET
GLASS WOOL PLUG
18/9 BALL JOINT
GAS EXIT
COOLING
WATER OUT
COOLING
WATER IN

Figure A-10. Glass wool SO_3/H_2SO_4 condenser.

The condenser was rinsed with approximately 50 milliliters of deionized water to remove any soluble sulfate. Condenser rinses were stored in polyethylene bottles until the sample could be analyzed for $SO_4^=$ by ion chromatography (Section A.4.2). The impingers were weighed to determine total mass increase for moisture calculations. The impinger solutions were than stored in polyethylene bottles until analyses could be performed by ion chromatography for SO_2 (as $SO_4^=$).

A.4 PROCESS SAMPLE COLLECTION AND ANALYSIS

A series of solid, liquid, and slurry scrubber samples were collected during this program. Chemical characterization of the various scrubber samples was used to evaluate the performance of the scrubber system. Samples included:

- raw quicklime feed,
- slaked lime slurry,
- recycle solids,
- atomizer feed slurry,
- spray dryer drop out solids,
- fabric filter solids, and
- makeup water.

A.4.1 Sample Collection

A grab sampling technique was used to collect each of the above scrubber samples. To help ensure that a representative sample was collected for analysis, the following precautions will be taken whenever applicable:

- All sample lines were purged prior to sample collection,

- Slurry samples were filtered as soon as possible to preserve sample integrity,

- Samples were stored in leak-tight labeled polyethylene bottles,

- A portion of the liquid samples was preserved for future chemical analysis.

- Upsets in system operation were considered in selecting representative sampling time periods.

A.4.2 Sample Analysis

A summary of the physical and chemical analyses that were performed on spray dryer process samples is provided in Table A-3. Table A-5 contains a summary of the analytical procedures used to determine each parameter of interest. A brief description of each of the anaytical methods is provided in the remainder of this section.

A.4.2.1 pH and Temperature

pH and temperature measurements were made on the raw unfiltered liquids and slurries using a portable pH meter and a mercury-in-glass thermometer at the sampling location. The meter was standardized at the sampling location immediately before each sample. The measurements were made while the sampling line was being purged, before other collection procedures.

A.4.2.2 Weight Percent Solids

Solids content of the slurries were determined gravimetrically. A measured weight of slurry was filtered through a tared filter paper. The solids were dried in an oven at 60°C overnight. The solids retained were saved after weighing for further analysis as required. Solids content was expressed using the dry solids weight as compared to the original sample, in terms of percent of the original weight.

TABLE A-5. SUMMARY OF PHYSICAL AND CHEMICAL ANALYSIS PROCEDURES

Measurement	Methodology
pH	pH meter
temperature	thermometer
weight % solids	gravimetric
% moisture	gravimetric
total solids	gravimetric/volumetric
% inerts	acid dissolution/gravimetric
Ca^{++}	atomic absorption
$SO_4^=$	ion chromatograph
$SO_3^=$	iodometric
$CO_3^=$	non-dispersive IR
lime reactivity	ASTM C110-76a
available lime index	ASTM C25-79

A.4.2.3 Moisture Content

Samples collected as solids were analyzed for moisture content. Small portions (1-2 g.) were weighed to the nearest 0.1 mg and dried overnight in an oven at 50°C to avoid loss of hydrates. Samples were desiccated and reweighed and moisture content calculated from the weight loss, as compared with the original sample weight.

A.4.2.4 Total Dissolved Solids

The total (dissolved) solids of the slurries was determined gravimetrically. An exactly measured aliquot (generally 50 ml) of the slurry filtrate from the weight percent solids determination was pipetted into a clean, dry, tared container and evaporated to dryness. Dissolved solids were expressed as the relative (percent) weight of the residue as compared to the weight of the filtrate, assuming a density of unity for the filtrate.

A.4.2.5 Inerts

The inerts content (acid insoluble fraction) of the solid samples was determined gravimetrically. A weighed portion (0.2-0.5 g) of the solid sample was transferred to a 250-ml volumetric flask containing about 50 ml DI H_2O with 1-2 ml of 30% H_2O_2. After the sample was suspended in the flask, the solution was acidified with 10 ml of 1 normal HCl, diluted to about 200 ml and stirred for at least 30 minutes. After stirring, the volume was brought up to exactly 250 ml with DI H_2O. After the solution was thoroughly mixed, it was filtered through a dried, tared 0.45-μm filter (Millipore HA, 47 mm). The filtrate was saved for Ca^{++}, Mg^{++}, and $SO_4^{=}$ analyses, while the filter was desiccated and reweighed to determine the acid insoluble fraction.

A.4.2.6 Calcium and Magnesium

Calcium and magnesium concentrations in solid samples were determined on site using a portable atomic absorption spectrometer and standard AA technique. The filtrate from the inerts determination was used for the calcium and magnesium analyses. Briefly, a liquid sample was aspirated into an air-acetylene flame through which passes a beam of electromagnetic radiation from an appropriate hollow-cathode lamp emitting a wavelength absorbed by the ground-state (unionized) atoms of interest. The beam then passed through a monochromater, which isolates the specific frequency and passes it to the detector. The absorbence of the unknown was compared to that of known standards to obtain concentration.

A.4.2.7 Sulfate

Sulfate concentration in the solid samples was determined on site using ion chromatography. An ion chromatograph separates the ionic species of the sample with ion-exchange columns and quantitates them using a conductrometric detector. The output from the instrument was recorded on a strip chart. The elution times for each peak were used to identify specific ions and peak heights are directly proportional to concentration. The unknown samples were compared with known standards. Again, the filtrate from the inerts determination was used for the soluble ionic analyses of the solids. The value obtained was the total sulfur (as sulfate) in the solids, since sulfite ($SO_3^=$) is oxidized to sulfate ($SO_4^=$) in the dissolution procedure with the addition of H_2O_2. The sulfate fraction in the original sample was determined by the difference in total sulfur (as sulfate) concentration and sulfite concentration.

A.4.2.8 Sulfite

Sulfite content of the solid samples was determined on site using an iodometric titration procedure. A solid sample (0.5-1.0 g) weighed to the nearest 0.1 mg was transferred to a prepared reaction bottle containing about 50 ml of pH 6 acetate buffer to which a known volume (typically 10 ml) of 0.1 N I_2 solution had been added volumetrically. The bottle was than sealed and the contents stirred vigorously for 10-15 minutes, after which the solution was titrated with 0.1 N $Na_2S_2O_3$ to a clear endpoint, using starch indicator. Blank solutions prepared in the same manner at the same time were also titrated, and the difference in titrant volumes (blank volume - sample volume) was used to calculate the sulfite concentration.

A.4.2.9 Carbonate

Carbonate analyses of the solid and liquid samples was performed using a non-dispersive infrared (NDIR) spectrometer. A sample was acidified in a reaction ampule and the CO_2 liberated carried to an IR cell by an inert purge gas (N_2). Interference from sulfite was minimized by the addition of H_2O_2 to the acid solution, and water vapor was removed from the gas stream before the sensor cell using anhydrone ($Mg(ClO_4)_2$) drying tubes. Unknown samples were compared to a known standard solution to determine concentration.

A.4.2.10 Lime Reactivity

The reactivity of the quicklime reagent was determined using the ASTM slaking rate test (11). According to this procedure, the increase in temperature caused by the exothermic reaction of quicklime with water is monitored carefully and the lime classified according to the rate, amount, and duration of the temperature increase.

A.4.2.11 Available Lime Index

The available lime index of the solid samples was determined using the standard ASTM procedure (12). According to this procedure, a sample is slaked completely by boiling in a relatively large volume of water. It is then cooled to room temperature, reacted with a neutralized sucrose solution, and titrated to the first phenylphthalein end point.

A.5 REFERENCES

1. "Standards of Performance for New Stationary Sources; Appendix B; Performance of Specifications 2 and 3 for SO_2, NO_x, CO_2, and O_2, Continuous Emission Monitoring Systems," Federal Register, Vol. 48, No. 102, May 25, 1983.

2. U.S. Environmental Research Information Center, U.S. Environmental Protection Agency, "Continuous Air Pollution Source Monitoring Systems - Handbook," EPA 625/6-79-005, Cincinnati, Ohio, June 1979.

3. EPA Method 4—"Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight," Environment Reporter, Bureau of National Affairs, Inc., December 5, 1980, pp. 121: 1574-1579.

4. EPA Method 3—"Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight," Environment Reporter, Bureau of National Affairs, Inc., December 5, 1980, pp. 121: 1571-1574.

5. EPA Method 6—"Determination of Sulfur Dioxide Emissions from Stationary Sources," Environment Reporter, Bureau of National Affairs, Inc., March 25, 1983, pp. 121: 1588-1591.

6. EPA Method 2—"Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S-Pitot Tube)," Environment Reporter, Bureau of National Affairs, Inc., December 5, 1980, pp. 121: 1563-1571.

7. EPA Method 1—"Sample and Velocity Traverse for Stationary Sources," Environment Reporter, Bureau of National Affairs, Inc., December 5, 1980, pp. 121: 1561-1563

8. EPA Method 17—"Determination of Particulate Emissions from Stationary Sources (In-Stack Filtration Method)," Environment Reporter, Bureau of National Affairs, Inc., March 25, 1983, pp 121: 1627-1639.

9. Maddalone, R. and N. Garner, "Process Measurement Procedures—Sulfuric Acid Emissions." TRW Document No. 28055-6004-RU-01, EPA Contract No. 68-02-2165, Task 13, Revised May 1977.

10. Cheney, J. and J. Homolya, "Characterization of Combustion Source Sulfate Emissions with a Selective Condensation Sampling System," in *Workshop Proceedings on Primary Sulfate Emissions from Combustion Sources, Vol. 1, Measurements Technology*. EPA 600/9-78-020a. NTIS PB287-436. Research Triangle Park, NC, EPA, ESRL, August 1978, pp. 53-62.

11. American Society for Testing and Materials, "Standard Methods of Physical Testing of Quicklime, Hydrated Lime, and Limestone," ANSI/ASTM C110-76a, Section 10.

12. American Society for Testing and Materials, "Chemical Analysis of Limestone, Quicklime, and Hydrated Lime," ANSI/ASTM C25-79, Section 28.

APPENDIX A-2

EXPERIMENTAL TECHNIQUES FOR THE SOLID WASTE CHARACTERIZATION

EXPERIMENTAL TECHNIQUES

Techniques used to determine chemical and physical characteristics of spray dryer products are outlined in the following paragraphs.

PARTICLE MORPHOLOGY

An Etec Omiscan scanning electron microscope (SEM) was used to characterize the morphology of particles of the dry scrubbing waste products. The voltage of the electron beam was 20.5 kV and the working distance was 14 mm. A small portion of each sample was mounted on an aluminum disc, coated with a gold-palladium alloy (60 percent gold, 40 percent palladium) and scanned to produce an electron micrograph.

CHEMICAL COMPOSITION OF SOLIDS

Spray dryer products were characterized by a series of laboratory tests for elemental compositions, crystalline species, and anionic species.

Elemental Composition

Elemental analyses were carried out on dry scrubbing waste products and extracts of the products using inductively coupled argon plasma emission spectrometry (ICP). This technique provided quantitative analysis of many elements at moderate cost. Concentrations of selected elements were measured in the extracts using atomic absorption spectrophotometry.

Solid samples were brought into solution using a digestion procedure employing a mixture of acids. The technique employed is similar to the procedure described by McQuaker, et al. (1), but differs in the amount of acid used. A known weight of sample is treated with a mixture of nitric and hydrofluoric acids and heated. Perchloric acid is added and the digestion is taken to dryness. The residue is dissolved using hydrochloric acid and diluted with deionized water to a known volume.

Analyses were carried out with an ARL Model 34,000 spectrometer. Samples in aqueous solution were aspirated into an argon plasma and the atomic emission pattern was recorded by a computer-controlled system. The computer system provided background correction, hard copy printout of results, and statistical analysis.

Detection limits of ICP for five of the eight trace elements for which primary maximum contaminant levels (MCLs) for public drinking water supplies have been promulgated are near or above the MCLs. These elements are: arsenic, cadmium, lead, mercury and selenium.

To be able to compare concentrations of these elements in extracts with drinking water standards, concentrations of these elements were measured using atomic absorption spectrophotometry. Detection limits for the twenty-eight elements measured are listed in Table A-6. Analyses by atomic absorption spectrophotometry were carried out in accordance with EPA's Methods for Chemical Analysis of Water and Waste (March 1979 (2).

Anionic concentrations of hydroxide, carbonate, sulfate, sulfite and chloride were then determined quantitatively by the following methods.

Hydroxide—

Hydroxide in the solids was determined using a modification of ASTM C-25, part 28, Available Lime Index. This method was developed to determine the free calcium oxide content of lime and hydrated lime.

The calcium in each sample was dissolved using a complexing sugar solution. The resultant solution was titrated with standardized

TABLE A-6. ELEMENTAL DETECTION LIMITS

Element	ICP[a] Detection Limit (mg/L in solution)	AA[b] Detection Limit (mg/L in solution)
Aluminum	0.050	
Antimony	0.030	
Arsenic	0.060	0.003
Barium	0.0006	
Beryllium	0.0005	
Boron	0.009	
Cadmium	0.008	0.0005
Calcium	0.040	
Chromium	0.001	
Cobalt	0.006	
Copper	0.001	
Iron	0.007	
Lead	0.080	0.002
Magnesium	0.030	
Manganese	0.001	
Mercury	0.030	0.0002
Molybdenum	0.002	
Nickel	0.003	
Potassium	0.040	
Selenium	0.080	0.004
Siver	0.002	
Sodium	0.005	
Strontium	0.001	
Thallium	0.090	
Tin	0.120	
Titanium	0.005	
Vanadium	0.003	
Zinc	0.03	

[a] Inductively coupled argon plasma emission spectrophotometer.

[b] Atomic absorption spectrophotometer.

hydrochloric acid as the pH was recorded to determine the titration curve. Any carbonates present in the dry scrubbing wastes were also titrated by this method. Therefore, the carbonatre concentration was determined by method given below and the appropriate equivalent of carbonate/bicarbonate was subtracted to yield an estimate of total hydroxides from this titration.

Carbonate--

About 200 mg of sample was placed in a one ounce linear polyethlene bottle and weighed to within 0.1 mg. A pH 10 buffer solution containing (EDTA) ammonium hydroxide, ammonium chloride and deionized water was added to fill the bottle. The mixture was agitated at least 4 hours (or 2 hours plus standing overnight). An aliquot of the supernatant liquor was injected into a nondispersive infrared analyzer manufactured by Oceanography International. The liquor entered a reaction chamber containing a solution buffered so that carbon dioxide was liberated, but sulfur dioxide was not liberated. A nitrogen carrier gas picked up the carbon dioxide and flowed through a dryer to remove moisture. The gas then flowed through an IR detection cell where the carbon dioxide content was measured. Solutions containing known amounts of carbonate were used as calibration standards.

Soluble Total Sulfur as Sulfate--

Soluble total sulfur in the spray dryer products were dissolved by controlled addition of hydrochloric acid to the solids, and diluting with deionized water. Sulfites in solution were oxidized to sulfate with hydrogen peroxide before acid was added. The solution was filtered and analyzed for sulfate concentration using a Dionex ion chromatograph. Solutions containing known amounts of sulfate were used as calibration standards.

Sulftate--

Sulfates in dry scrubbing waste products were calculated by subtracting sulfite concentration from the total sulfur concentration. Radian has found all specific sulfate techniques unsuitable because they suffer from sulfite interference.

Sulfite--

Sulfite concentrations were measured using an iodine titration. A weighed solid sample was added to a standard volume of iodine solution buffered at pH 6 with sodium acetate and acetic acid. The container was securely closed and the mixture was stored for 15 minutes to allow sulfite to dissolve and react with the iodine. Unreacted iodine was back titrated with standard thiosulfate and the sulfite concentration calculated.

Soluble Chloride--

Chloride in the dry scrubbing waste products was brought into solution by water dissolution of the solids. The solutions were anlayzed for chloride concentrations by using a Dionex ion Chromatograph and standard solutions containing known amounts of chloride for calibration.

CHEMICAL COMPOSITION OF EXTRACTS

The spray dryer solids were extracted by two methods: the EPA Extraction Procedure, and the same procedure without acid addition (neutral extract).

The EP Extraction Procedure was designed as a simple, reproducible test to evaluate the potential for a solid waste to contaminate the groundwater. The results of the chemical anlaysis on the extract are compared with 100 times primary maximum contaminant levels for public drinking water supplies. If any element exceeds this level, then the waste is classified as hazardous. The procedure is described in the May 19, 1980 Federal Register (3).

The second extraction was performed using deionized water with no pH adjustments. The pH of this extraction was the natural pH of the solid waste in contact with water. All other aspects of this procedure were the same as the EP procedure. The extracts are referred to as neutral leachates.

Elemental Composition

The same ICP elemental analyses were performed on the RCRA extracts and neutral extracts that were performed on the solids.

Water Quality Parameters

Values of pH in RCRA extracts were determined using a standardized pH meter. Conductivity was measured in neutral extracts using a conductivity meter. Dissolved solids content was determined on neutral leachates using gravimetric analysis.

Total Sulfur as Sulfate

Total sulfur in the neutral and RCRA leachates of the spray dryer products were determined by a Dionex ion chromatograph. Sulfites in solution were oxidized to sulfates by the addition of hydrogen peroxide. Solutions containing known amounts of sulfate were used as calibration standards.

Fluoride

Fluoride concentrations were determined by Method 413B, Standard Methods for the Examination of Water and Wastewater, 15th Edition (4), using an ion specific electrode for fluoride.

Chloride

Chloride concentrations in the leachates of dry scrubbing waste products were determined by the same analytical methods used for the chloride determination with the solids.

OTHER TESTS

Several other analytical techniques were performed to identify pertinent chemical and physical properties of the dry scrubbing waste products. These tests included moisture determination, insoluble material determination, strength development measurements and permeability tests.

Percent Moisture

Percent moisture was determined gravimetrically. Approximately 500 mg of sample was weighed to the nearest 0.1 mg. Samples were dried for four hours at 50°C, cooled in a desiccator for one hour and reweighed. This gentle drying procedure avoided dehydration of species containing chemically bound water of hydration.

Acid and Water Insolubles

Fractions of acid insoluble material and water insoluble material were determined in this task. Acid insolubles were determined using the procedure outlined in the following paragraph.

About one gram of solid sample was weighed to the nearest 0.1 mg and transferred to a 500 mL volumetric flask. The flask contained approximately 400 mL deionized water and a magnetic stir bar. Ten mL of 3 percent hydrogen peroxide solution was pipetted into a flask and the resulting mixture was stirred for an additional 30 minutes. Twenty mL of 12 molar hydrochloric acid were added using a graduated cylinder and the acidified slurry was stirred another 30 minutes. After the stirring bar was removed, the slurry was diluted to 500 mL with deionized water and filtered. A preweighed filter membrane with a pore size of 0.45 μm was used. The collected solids were dried to constant weight (±0.5 mg) at 50°C. Filtrate from the acid dissolution was analyzed for total sulfur as sulfate.

Water insolubles were determined by adding one gram of sample to about 430 mL of deionized water, closing the flask and stirring for one hour and ten minutes. Dilution to volumes, filtration and determination of insolubles were carried out in the same manner as they were for the acid dissolution. The filtrate was analyzed for chloride.

Measurement of Strength Development

Strength development resulting from compaction and hydration reaction was determined. Powders were mixed with water in known proportions, compacted into cylinders, and cured. The compaction cylinders were three inches in diameter and six inches high. Test mixtures were compacted in three layers. Each layer received 16 blows from a 5.4 pound hammer dropped 12 inches. Curing consisted of keeping the cylinders at 25°C and 100 percent relative humidity for four weeks and eight weeks. Unconfined compressive strength was determined on cured cylinders according to ASTM Method D-1633.

Permeability Coefficients

Permeability coefficients were made on cylinders of dry scrubbing product that had been mixed with water at estimated optimum moisture content, compacted, sealed and cured in a humidity chamber at room temperature for four weeks. Permeability coefficients were determined using a permeameter similar in design to that described in the U.S. Army Corps of Engineers Manual (5). Leachate was collected in a container protected from the ambient air by a water trap. Permeability calculations were based on the amount of leachate collected and the hydraulic gradient applied.

REFERENCES

1. McQuaker, et al, "Digestion of Environmental Materials for Analysis by Inductively Coupled Plasma-Atomic Emission Spectrometry," Analytical Chemistry 51 (7) 1082-84, 1979.

2. Methods for Chemical Analysis of Water and Wastes. Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, EPA-600/4-79-020, March 1979.

3. Federal Register 45 (98), 33127, May 19, 1980.

4. Greenberg, A.E., J.J. Connors, and D. Jenkins, eds. Standard Methods for the Examination of Water and Wastewater, 15th Edition, American Public Health Association, 1015 Fifteenth St., NW, Washington, DC, 20005, 1980.

5. Laboratory Soils Testing, Engineer Manual, EM 1110-2-1906, Appendix VII, Headquarters, Department of the Army Office of the Chief of Engineers, 1970.

APPENDIX B

COAL ANALYSES

This appendix includes the results of coal sample ultimate, proximate, and ash analyses. The analyses were subcontracted to Hazen Research, Inc., in Golden, Colorado. Samples R-001 through R-003 were collected during the high sulfur coal portion of this test program, while samples R-004 through R-006 were collected during the low sulfur coal portion.

Correction to Report
dated November 7, 1983

HAZEN

Hazen Research, Inc.
4601 Indiana St • Golden, Colo. 80401
Tel: (303) 279-4501 • Telex: 45-860

DATE November 17, 1983
HRI PROJECT 002-88K
HRI SERIES NO. 26574-1
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-001

-

REPORTING BASIS >	AS RECD	DRY	EQM	AIR DRY
PROXIMATE (%)				
MOISTURE	13.12	0.00		3.13
ASH	11.46	13.19		12.78
VOLATILE	33.26	38.29		37.09
FIXED C	42.16	48.52		47.00
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
SULFUR	2.95	3.40		3.29
BTU/LB	10719	12338		11952
MMF BTU/LB		14506		
MAF BTU/LB		14213		
AIR DRY LOSS (%)	10.32			
ULTIMATE (%)				
MOISTURE	13.12	0.00		3.13
CARBON	59.46	68.44		66.30
HYDROGEN	4.29	4.93		4.78
NITROGEN	0.94	1.08		1.05
SULFUR	2.95	3.40		3.29
ASH	11.46	13.19		12.78
OXYGEN*	7.78	8.96		8.67
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
CHLORINE**				
FORMS OF SULFUR (AS S,%)				
SULFATE				
PYRITIC				
ORGANIC				
	------	------		
TOTAL	2.95	3.40		
WATER SOLUBLE ALKALIES (%)				
NA2O				
K2O				

HGI= @ % MOISTURE
AS REC'D SP.GR. (G/CC)
FREE SWELLING INDEX

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

* OXYGEN BY DIFFERENCE.
** NOT USUALLY REPORTED AS PART OF THE ULTIMATE ANALYSIS

HAZEN

Hazen Research, Inc.
4601 Indiana St • Golden, Colo. 80401
Tel: (303) 279-4501 • Telex: 45-860

DATE	November 7, 1983
HRI PROJECT	002-88K
HRI SERIES NO	26574-1
DATE RECD	10/21/83
CUST P.O.#	H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-001

-

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	49.36
AL2O3	18.16
TIO2	0.64
FE2O3	15.72
CAO	6.27
MGO	0.95
NA2O	0.76
K2O	1.87
P2O5	0.26
SO3	5.93
TOTAL	99.92

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL		
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	27.28
ACID CONTENT (%)	72.72
DOLOMITE RATIO	28.24
BASE/ACID RATIO	0.38
SILICA/ALUMINA RATIO	2.72
T(CV),DEG F	
T250 TEMPERATURE (DEG F)	2437
EQUIV SILICA CONTENT (%)	68.27
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	113.40
ASH TYPE	HIGH RANK

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

---

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'.
W.L. SAGE AND J.B. MCILROY,1960.

Correction to Report
dated November 7, 1983

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DATE November 17, 1983
HRI PROJECT 002-88K
HRI SERIES NO. 26564-2
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-002

-

REPORTING BASIS >	AS RECD	DRY	EQM	AIR DRY
PROXIMATE (%)				
MOISTURE	14.52	0.00		2.42
ASH	10.83	12.67		12.36
VOLATILE	33.51	39.20		38.25
FIXED C	41.14	48.13		46.97
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
SULFUR	3.37	3.95		3.85
BTU/LB	10620	12423		12123
MMF BTU/LB		14529		
MAF BTU/LB		14225		
AIR DRY LOSS (%)	12.40			
ULTIMATE (%)				
MOISTURE	14.52	0.00		2.42
CARBON	58.39	68.31		66.66
HYDROGEN	4.15	4.86		4.74
NITROGEN	0.93	1.09		1.06
SULFUR	3.37	3.95		3.85
ASH	10.83	12.67		12.36
OXYGEN*	7.81	9.12		8.91
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
CHLORINE**				
FORMS OF SULFUR (AS S,%)				
SULFATE				
PYRITIC				
ORGANIC				
	------	------		
TOTAL	3.37	3.95		

HGI= @ % MOISTURE
AS REC'D SP.GR. (G/CC)
FREE SWELLING INDEX

REPORT PREPARED BY:

WATER SOLUBLE ALKALIES (%)

NA2O
K2O

JUDITH H. FIFE
COAL LABORATORY MANAGER

* OXYGEN BY DIFFERENCE.
** NOT USUALLY REPORTED AS PART OF THE ULTIMATE ANALYSIS

HAZEN
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DATE	November 7, 1983
HRI PROJECT	002-88K
HRI SERIES NO	26564-2
DATE RECD	10/21/83
CUST P.O.#	H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-002

-

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	47.25
AL2O3	17.69
TIO2	0.66
FE2O3	16.35
CAO	6.17
MGO	0.99
NA2O	0.75
K2O	1.75
P2O5	0.17
SO3	6.75
TOTAL	98.53

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL		
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	28.39
ACID CONTENT (%)	71.61
DOLOMITE RATIO	27.53
BASE/ACID RATIO	0.40
SILICA/ALUMINA RATIO	2.67
T(CV),DEG F	
T250 TEMPERATURE (DEG F)	2409
EQUIV SILICA CONTENT (%)	66.78
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	89.96
ASH TYPE	HIGH RANK

REPORT PREPARED BY:

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COAL LABORATORY MANAGER

---

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

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DATE November 7, 1983
HRI PROJECT 002-88K
HRI SERIES NO. 26574-3
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-003

-

REPORTING BASIS >	AS RECD	DRY	EQM	AIR DRY
PROXIMATE (%)				
MOISTURE	13.73	0.00		2.85
ASH	10.28	11.92		11.58
VOLATILE	34.11	39.54		38.41
FIXED C	41.88	48.54		47.16
	-------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
SULFUR	3.12	3.61		3.51
BTU/LB	10792	12510		12154
MMF BTU/LB		14482		
MAF BTU/LB		14203		
AIR DRY LOSS (%)	11.20			
ULTIMATE (%)				
MOISTURE	13.73	0.00		2.85
CARBON	59.69	69.19		67.22
HYDROGEN	4.29	4.97		4.83
NITROGEN	0.99	1.14		1.11
SULFUR	3.12	3.61		3.51
ASH	10.28	11.92		11.58
OXYGEN*	7.90	9.17		8.90
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
CHLORINE**				
FORMS OF SULFUR (AS S,%)				
SULFATE				
PYRITIC				
ORGANIC				
	------	------		
TOTAL	3.12	3.61		
WATER SOLUBLE ALKALIES (%)				
NA2O				
K2O				

HGI= @ % MOISTURE
AS REC'D SP.GR. (G/CC)
FREE SWELLING INDEX

REPORT PREPARED BY:

-----------------------------
JUDITH H. FIFE
COAL LABORATORY MANAGER

* OXYGEN BY DIFFERENCE.
** NOT USUALLY REPORTED AS PART OF THE ULTIMATE ANALYSIS

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DATE	November 7, 1983
HRI PROJECT	002-88K
HRI SERIES NO	26574-3
DATE RECD	10/21/83
CUST P.O.#	H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-003

-

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	48.91
AL2O3	18.05
TIO2	0.74
FE2O3	15.82
CAO	5.40
MGO	1.02
NA2O	0.71
K2O	1.87
P2O5	0.17
SO3	5.32
TOTAL	98.01

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL		
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	26.83
ACID CONTENT (%)	73.17
DOLOMITE RATIO	25.87
BASE/ACID RATIO	0.37
SILICA/ALUMINA RATIO	2.71
T(CV),DEG F	
T250 TEMPERATURE (DEG F)	2448
EQUIV SILICA CONTENT (%)	68.74
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	122.46
ASH TYPE	HIGH RANK

REPORT PREPARED BY:

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* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

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DATE November 17, 1983
HRI PROJECT 002-88K
HRI SERIES NO. 26574-4
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-004
-

REPORTING BASIS >	AS RECD	DRY	EQM	AIR DRY
PROXIMATE (%)				
MOISTURE	22.77	0.00		7.95
ASH	10.29	13.32		12.26
VOLATILE	26.23	33.96		31.26
FIXED C	40.71	52.72		48.53
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
SULFUR	2.20	2.85		2.62
BTU/LB	9098	11780		10843
MMF BTU/LB		13846		
MAF BTU/LB		13590		
AIR DRY LOSS (%)	16.10			
ULTIMATE (%)				
MOISTURE	22.77	0.00		7.95
CARBON	52.47	67.93		62.53
HYDROGEN	3.26	4.23		3.89
NITROGEN	0.66	0.86		0.79
SULFUR	2.20	2.85		2.62
ASH	10.29	13.32		12.26
OXYGEN*	8.35	10.81		9.96
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
CHLORINE**				
FORMS OF SULFUR (AS S,%)				
SULFATE				
PYRITIC				
ORGANIC				
	------	------		
TOTAL	2.20	2.85		
WATER SOLUBLE ALKALIES (%)				
NA2O				
K2O				

HGI= @ % MOISTURE
AS REC'D SP.GR. (G/CC)
FREE SWELLING INDEX

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

* OXYGEN BY DIFFERENCE.
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Hazen Research, Inc.
4601 Indiana St • Golden, Colo. 80401
Tel: (303) 279-4501 • Telex: 45-860

DATE November 7, 1983
HRI PROJECT 002-88K
HRI SERIES NO 26574-4
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-004
-

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	30.43
AL2O3	14.43
TIO2	0.57
FE2O3	17.55
CAO	14.30
MGO	2.55
NA2O	1.20
K2O	0.62
P2O5	0.23
SO3	17.87
TOTAL	99.75

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL		
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	44.36
ACID CONTENT (%)	55.64
DOLOMITE RATIO	46.52
BASE/ACID RATIO	0.80
SILICA/ALUMINA RATIO	2.11
T(CV),DEG F	
T250 TEMPERATURE (DEG F)	2185
EQUIV SILICA CONTENT (%)	46.94
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	5.96
ASH TYPE	HIGH RANK

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

---

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH': A.F. DUZY,1965.
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W.L. SAGE AND J.B. MCILROY,1960.

HAZEN

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Tel: (303) 279-4501 • Telex: 45-860

DATE November 7, 1983
HRI PROJECT 002-88K
HRI SERIES NO. 26574-5
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-005

-

REPORTING BASIS >	AS RECD	DRY	EQM	AIR DRY
PROXIMATE (%)				
MOISTURE	21.96	0.00		10.05
ASH	10.61	13.60		12.23
VOLATILE	28.26	36.21		32.57
FIXED C	39.17	50.19		45.15
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
SULFUR	1.52	1.95		1.75
BTU/LB	9185	11769		10586
MMF BTU/LB		13854		
MAF BTU/LB		13621		
AIR DRY LOSS (%)	13.24			
ULTIMATE (%)				
MOISTURE	21.96	0.00		10.05
CARBON	52.79	67.64		60.84
HYDROGEN	3.29	4.22		3.80
NITROGEN	0.63	0.81		0.73
SULFUR	1.52	1.95		1.75
ASH	10.61	13.60		12.23
OXYGEN*	9.20	11.78		10.60
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
CHLORINE**				
FORMS OF SULFUR (AS S,%)				
SULFATE				
PYRITIC				
ORGANIC				
	------	------		
TOTAL	1.52	1.95		

HGI= @ % MOISTURE
AS REC'D SP.GR. (G/CC)
FREE SWELLING INDEX

REPORT PREPARED BY:

WATER SOLUBLE ALKALIES (%)

NA2O
K2O

JUDITH H. FIFE
COAL LABORATORY MANAGER

* OXYGEN BY DIFFERENCE.
** NOT USUALLY REPORTED AS PART OF THE ULTIMATE ANALYSIS

Hazen Research, Inc.
4601 Indiana St • Golden, Colo. 80401
Tel: (303) 279-4501 • Telex: 45-860

DATE	November 7, 1983
HRI PROJECT	002-88K
HRI SERIES NO	26574-5
DATE RECD	10/21/83
CUST P.O.#	H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-005

-

ELEMENTAL ANALYSIS OF ASH (%)

SiO_2	34.92
Al_2O_3	15.38
TiO_2	0.56
Fe_2O_3	9.38
CAO	15.71
MGO	2.05
Na_2O	2.24
K_2O	1.13
P_2O_5	0.40
SO_3	18.48
TOTAL	100.25

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL		
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	37.50
ACID CONTENT (%)	62.50
DOLOMITE RATIO	58.21
BASE/ACID RATIO	0.60
SILICA/ALUMINA RATIO	2.27
T(CV),DEG F	
T250 TEMPERATURE (DEG F)	2250
EQUIV SILICA CONTENT (%)	56.27
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	19.40
ASH TYPE	LIGNITE

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

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* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965. 'RELATIONSHIP OF COAL-ASH VISCOSITY TO CHEMICAL COMPOSTION'. W.L. SAGE AND J.B. MCILROY,1960.

HAZEN

Hazen Research, Inc.
4601 Indiana St • Golden, Colo. 80401
Tel: (303) 279-4501 • Telex: 45-860

DATE November 7, 1983
HRI PROJECT 002-88K
HRI SERIES NO. 26574-6
DATE RECD 10/21/83
CUST P.O.# H18540

REPORT OF ANALYSIS
Radian Corporation
Mr. Eric Anderson
Post Office Box 9948
Austin Texas 78766

SAMPLE IDENTIFICATION:
R-006

-

REPORTING BASIS >	AS RECD	DRY	EQM	AIR DRY
PROXIMATE (%)				
MOISTURE	21.66	0.00		5.79
ASH	12.57	16.04		15.11
VOLATILE	28.02	35.76		33.69
FIXED C	37.75	48.20		45.41
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
SULFUR	1.07	1.37		1.29
BTU/LB	8695	11098		10456
MMF BTU/LB		13463		
MAF BTU/LB		13218		
AIR DRY LOSS (%)	16.84			
ULTIMATE (%)				
MOISTURE	21.66	0.00		5.79
CARBON	51.01	65.11		61.34
HYDROGEN	3.27	4.17		3.93
NITROGEN	0.63	0.81		0.76
SULFUR	1.07	1.37		1.29
ASH	12.57	16.04		15.11
OXYGEN*	9.79	12.50		11.78
	------	------	------	------
TOTAL	100.00	100.00	100.00	100.00
CHLORINE**				
FORMS OF SULFUR (AS S,%)				
SULFATE				
PYRITIC				
ORGANIC				
	------	------		
TOTAL	1.07	1.37		
WATER SOLUBLE ALKALIES (%)				
NA2O				
K2O				

HGI= @ % MOISTURE
AS REC'D SP.GR. (G/CC)
FREE SWELLING INDEX

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

* OXYGEN BY DIFFERENCE.
** NOT USUALLY REPORTED AS PART OF THE ULTIMATE ANALYSIS

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-

ELEMENTAL ANALYSIS OF ASH (%)

SIO2	31.67
AL2O3	14.54
TIO2	0.58
FE2O3	3.97
CAO	26.40
MGO	1.78
NA2O	1.92
K2O	1.28
P2O5	0.30
SO3	15.44
TOTAL	97.88

ASH FUSION TEMPERATURES (DEG F)

	OXIDIZING ATMOSPHERE	REDUCING ATMOSPHERE
INITIAL		
SOFTENING		
HEMISPHERICAL		
FLUID		

ASH VISCOSITY CALCULATIONS *

BASE CONTENT (%)	43.04
ACID CONTENT (%)	56.96
DOLOMITE RATIO	79.72
BASE/ACID RATIO	0.76
SILICA/ALUMINA RATIO	2.18
T(CV),DEG F	
T250 TEMPERATURE (DEG F)	2176
EQUIV SILICA CONTENT (%)	49.62
VISCOSITY FROM EQUIV SILICA (POISE),2600 F	8.22
ASH TYPE	LIGNITE

REPORT PREPARED BY:

JUDITH H. FIFE
COAL LABORATORY MANAGER

---

* 'FUSIBILITY-VISCOSITY OF LIGNITE-TYPE ASH'. A.F. DUZY,1965.
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W.L. SAGE AND J.B. MCILROY,1960.

APPENDIX C

CONVERSION FACTORS

The conversion factors in Table C-1 can be used to convert values in British engineering (English) units to equivalent values in SI units.

TABLE C-1. CONVERSION OF BRITISH ENGINEERING (ENGLISH) UNITS TO SI UNITS

To Obtain	From	Multiply by (or use equation)
ng/J	lb/10^6 Btu	430
m	ft	0.3048
m^2	ft^2	9.29×10^{-2}
m^3	ft^3	2.83×10^{-2}
mg/Nm^3	gr/dscf	1.83
°C	°F	t_c (°C) = 5/9[t_f(°F) - 32]
kW	hp	0.746
joules/kg	Btu/lb	1.33×10^{-4}
m^3/sec/m^2	cfm/ft^2	5.08×10^{-3}
tonnes	tons (short)	0.907
kg	lb	0.454
m^3/sec	cfm	4.72×10^{-4}
m^3/sec	gpm	6.31×10^{-5}

APPENDIX D
DATA QUALITY

The test approach used during this project for dry FGD system characterization incorporated a comprehensive quality assurance/quality control (QA/QC) program as part of the continuous monitoring and sampling and analytical effort. The QA/QC program was designed to ensure that the SO_2 removal efficiency and lime utilization data collected during the test program were complete, representative, and comparable to other similar data. It was also designed to control measurement data quality within prescribed limits of acceptability and to ensure that the resulting data were of known quality with respect to precision and accuracy.

The QA/QC efforts primarily addressed the continuous monitors, which were used to quantify SO_2 removal efficiencies, and calcium and sulfate ion concentration measurements, which were used to calculate lime reagent ratios and corresponding utilization values. The results of these efforts are summarized in the following subsections. Subsection D-1 presents QC data, while subsection D-2 summarizes the results of a QA audit conducted near the middle of the program.

D.1 QC DATA

As mentioned above, the QC efforts for this test program were centered on continuous emissions monitoring system (CEMS) results and on calcium and sulfate ion concentration measurements. These data were used to quantify the primary measurement goals of this test program: SO_2 removal efficiency and lime reagent ratio requirements.

D.1.1 QC Efforts for the CEMS

QC efforts for the CEMS included daily span and zero drift check on each of the four monitors and a daily QC gas measurements (after any span or zero adjustments required). Table D-1 summarizes daily span and zero drift measurements for the four monitors during the low sulfur coal portion of the test program. Data are presented from 7/7/83, but only CEMS results from 7/25/83 were used in this report. Consequently, averages and standard deviations presented include only data from 7/25.

For the extractive DuPont SO_2 and Thermox O_2 monitoring system at the spray dryer inlet, zero and span gases were introduced through a three-way valve mounted in-line between the sample probe inserted into the inlet duct and the heat-traced sampled line. Thus the effects of the entire sample system other than the in-stack probe were included. Zero and span gases were occasionally introduced through the sample system for the spray dryer outlet. For the in-situ Lear-Siegler SO_2 and Thermox O_2 monitors at the fabric filter outlet location, zero and span gases were introduced at external ports which were plumbed into the measurement cells of each monitor. The rates at which these gases were introduced were controlled at constant, relatively low values in order to avoid pressurizing the cells to above-stack levels.

For the extractive spray dryer inlet monitors, the zero and span drift measurements were conducted virtually every day the test crew was on-site. Exceptions were days when the unit was off-line for the entire period of daylight hours. For the in-situ fabric filter outlet monitors, zero and span drift measurements were conducted only on days when the unit was at the desired operating conditions of 60 MW or greater and with the spray dryer at a 20°F approach to saturation (based on wet bulb measurements at the fabric filter outlet). This was because the span of both monitors was affected by stack pressure (partial pressures of SO_2 and O_2), and the Lear-Siegler SO_2 monitor span was affected by stack temperature as well. Although the Lear-Siegler SO_2 monitor had an integral electronic temperature

TABLE D-1. DAILY CEMS SPAN AND ZERO DRIFT MEASUREMENTS DURING LOW SULFUR COAL TESTING

Date	Spray Dryer Inlet								Fabric Filter Outlet							
	DuPont SO2 Monitor				Thermox O2 Monitor				Lear-Siegler				Thermox O2 Monitor			
	Zero Value (ppm)	Drift (%)	Span Value (ppm)	Drift (%)	Zero Value (ppm)	Drift (%)	Span Value (ppm)	Drift (%)	Zero Value (ppm)	Drift (%)	Span Value (ppm)	Drift (%)	Zero Value (ppm)	Drift (%)	Span Value (ppm)	Drift (%)
7/7	3	0.3	1191	0.1	0.5	0.0	20.9	0.0	-1	-0.1	605	-0.9	0.6	0.1	20.9	0.0
7/11	3	0.3	1114	-6.3	0.2	-0.3	20.9	0.0								
7/12	5	0.4	1189	-0.1	0.2	-0.3	21.0	0.1	-5	-0.5	631	1.7	0.5	0.0	21.3	0.4
7/13	-10	-0.8	1148	-3.5	0.3	-0.2	20.7	-0.2					0.6	0.1	21.2	0.3
7/14	6	0.5	1204	1.2	0.1	-0.4	21.1	0.2	4	0.4	606	-0.8				
7/15	5	0.4	1220	2.5	0.2	-0.3	20.6	-0.3	1	0.1	591	-2.3	0.6	0.1	21.0	0.1
7/16	0	0.0	1229	3.3	0.4	-0.1	20.6	-0.3								
7/17	5	0.4	1113	-6.4	0.5	0.0	20.5	-0.4								
7/18	-7	-0.6	1300	9.2	0.5	0.0	20.8	-0.1								
7/19					0.2	-0.3	20.9	0.0					0.7	0.2	21.0	0.1
7/20	-8	-0.7	1205	1.3	0.1	-0.4	21.0	0.1					0.6	0.1	21.4	0.5
7/21	5	0.4	1172	-1.5	0.7	0.2	20.5	-0.4	3	0.3	620	0.6	0.7	0.2	20.6	-0.3
7/22	9	0.8	1139	-4.3	0.2	-0.3	20.8	-0.1								
7/23	25	2.1	1186	-0.3	0.1	-0.4	20.5	-0.4					0.6	0.1	20.9	0.0
7/24	7	0.6	1230	3.3	0.7	0.2	21.0	0.1								
7/25	6	0.5	1218	2.3	0.2	-0.3	21.1	0.2	5	0.5	625	1.1	0.7	0.2	20.8	-0.1
7/26	-17	-1.4	1183	-0.6	0.2	-0.3	21.1	0.2								
7/27	8	0.7	1195	0.4	0.2	-0.3	21.1	0.2								
7/28	9	0.8	1152	-3.2	0.2	-0.3	21.3	0.4	-3	-0.3	613	-0.1				
7/29	6	0.5	1141	-4.1	0.4	-0.1	20.9	0.0								
7/30	20	1.7	1222	2.7	0.2	-0.3	21.0	0.1	3	0.3	640	2.6				
8/1	11	0.9	1228	3.2	0.2	-0.3	21.3	0.4	0	0.0	610	-0.4	0.7	0.2	21.3	0.4
8/2	-9	-0.8	1165	-2.1	0.2	-0.3	21.2	0.3	3	0.3	613	-0.1	0.7	0.2	20.6	-0.3
8/4	-3	-0.3	1189	-0.1	0.2	-0.3	21.2	0.3	0	0.0	623	0.9	0.5	0.0	21.1	0.2
8/5	7	0.6	1141	-4.1	0.2	-0.3	21.4	0.5	-3	-0.3	633	1.9	0.9	0.4	21.0	0.1
8/6	7	0.6	1202	1.0	0.2	-0.3	21.3	0.4	3	0.3	633	1.9	0.7	0.2	20.9	0.0
8/8	6	0.5	1179	-0.9	0.2	-0.3	21.0	0.1	0	0.0	623	0.9	0.8	0.3	21.0	0.1
8/9	4	0.3	1200	0.8	0.2	-0.3	21.4	0.5	0	0.0	613	-0.1	0.8	0.3	21.1	0.2
8/10	3	0.3	1187	-0.3	0.2	-0.3	21.9	1.0	-3	-0.3	623	0.9	0.6	0.1	21.2	0.3
8/11	6	0.5	1201	0.9	0.2	-0.3	20.9	0.0								
8/15	0	0.0	1154	-3.0	0.5	0.0	20.8	-0.1					1.1	0.6	21.0	0.1
8/16	0	0.0	1181	-0.8	0.3	-0.2	20.5	-0.4	0	0.0	618	0.4	0.7	0.2	21.2	0.3
8/17	4	0.3	1195	0.4	0.2	-0.3	20.9	0.0	0	0.0	620	0.6	0.5	0.0	20.6	-0.3
8/18	3	0.3	1187	-0.3	0.4	-0.1	21.0	0.1								
8/19	3	0.3	1200	0.8	0.2	-0.3	20.8	-0.1	0	0.0	600	-1.4	0.6	0.1	20.2	0.3
8/22	6	0.5	1212	1.8	0.2	-0.3	21.0	0.1	0	0.0	645	3.1	0.6	0.1	21.2	0.3
8/23	3	0.3	1214	2.0	0.2	-0.3	21.1	0.2	0	0.0	618	0.4	0.6	0.1	21.2	0.3
8/25	6	0.5	1214	2.0	0.2	-0.3	21.0	0.1	0	0.0	620	0.6	0.7	0.2	20.8	-0.1
8/26	4	0.3	1197	0.6	0.2	-0.3	21.0	0.1	0	0.0	628	1.4	0.9	0.4	20.8	-0.1
8/29	1	0.1	1191	0.1	0.3	-0.2	21.0	0.1	0	0.0	605	-0.9	1.0	0.5	20.8	-0.1
8/30	4	0.3	1191	0.1	0.3	-0.2	21.2	0.3	0	0.0	628	1.4	0.8	0.3	20.8	-0.1
Average (from 7/25)	3.8	0.3	1190.0	.0	0.2	-0.3	21.1	0.2	0.3	.0	621.6	0.8	0.7	0.2	20.9	0.1
Std. Dev. (from 7/25)	6.5	0.5	23.1	1.9	0.1	0.1	0.3	0.3	2.0	0.2	10.9	1.1	0.2	0.2	0.3	0.2
Actual Value	0	-	1190	-	0.5	-	20.9	-	0	-	614	-	0.5	-	20.9	-

correction circuit, it was felt to be most appropriate to conduct these zero and span drift measurements at exactly the same operating conditions as the actual stack concentration measurements of interest. This approach did not have a negative effect on the quality of the data presented in this report, because by definition no data were included in the test means presented in Section 5 for days when zero and span drift measurements could not be made.

For the SO_2 zero and span drift measurements, drift was calculated by the following equation:

$$\text{Drift (\%)} = \frac{\text{CEMS response (ppm) - Certified Gas Conc. Value (ppm)}}{\text{Instrument Full-Scale Span Value (ppm)}} \times 100 \qquad \text{(D-1)}$$

For the low sulfur coal test period, the DuPont inlet SO_2 monitor full-scale span value was 1200 ppm, and the Lear-Siegler outlet SO_2 monitor full-scale span value was 1000 ppm. The O_2 drift for both locations was calculated as follows:

$$\text{Drift (\%}O_2\text{)} = \text{CEMS Response (\% }O_2\text{)} - \text{Certified Gas Conc. Value (\% }O_2\text{)} \qquad \text{(D-2)}$$

In Table D-1, the results show that for the DuPont inlet SO_2 monitor, zero drift never exceeded the control level of ±2.5 percent of scale. In fact, the average drift was only 0.3 percent and the standard deviation was 0.5 percent. Only two values exceeded ±1.0 percent from 7/25 through the end of the low sulfur coal test period. The span drift averaged 0.0 percent, with a standard deviation of 1.9 percent. From 7/25, only six values exceeded the drift control limit of ±2.5 percent of the full-scale span and required span adjustment.

The inlet Thermox O_2 monitor showed an average zero drift of -0.3 percent O_2 with a standard deviation of 0.1 percent O_2 and an average span drift of 0.2 percent O_2 with a standard deviation of 0.3 percent O_2. No zero drift values and only one span drift value after 7/25 exceeded the control limit of ±0.5 percent O_2.

For the fabric filter outlet location, the Lear-Siegler SO_2 monitor also exhibited very small zero drift values. The average was 0.0 percent drift, with a standard deviation of 0.2. The span drift averaged 0.8 percent of full-scale, with a standard deviation of 1.1 percent. Only two values after 7/25 exceeded the control limit of ±2.5 percent of full scale.

The outlet Thermox O_2 monitor averaged 0.2 percent O_2 for zero drift, with a standard deviation of 0.2 percent O_2. The span drift averaged 0.1 percent O_2 with a 0.2 percent O_2 standard deviation. Only one zero drift value and no span drifted value exceeded the 0.5 percent O_2 control limit.

Table D-2 summarizes the zero and span drift values for the high sulfur coal test period. During this test period, full scale for the inlet DuPont SO_2 monitor was 3200 ppm, while full scale for the outlet remained at 1000 ppm. At the spray dryer inlet, zero drift averaged 0.1 percent with a standard deviation of 0.1 percent, and the calculated span drift averaged -2.6 percent with a standard deviation of 2.2 percent. However, this span drift value does not actually reflect instrument drift in this particular case, but rather reflects an effort to compensate for an observed non-linearity of instrument response. The drift calculation is intended to quantify the difference in instrument response at two points in time. It assumes that at some initial point, the instrument is set to read a concentration corresponding to that of the span gas. Deviation from this set point is then quantified as drift. However, for most of the high sulfur coal test period, the inlet SO_2 instrument was found to have a slightly non-linear response to SO_2 concentrations above approximately 2000 ppm. If the instrument span was set to read correctly using the 3161 ppm span gas, this induced error of more than ±1.0 percent for the 2087 ppm QC gas. Since the normal inlet concentration was near 2000 ppm, it was decided to set the instrument span to read about 3080 ppm for the 3161 ppm gas. This compensated for the slight non-linearity of response and improved accuracy in the range of most of the measurement data. The instrument linearity problem was corrected by cleaning several quartz lenses just after the zero and span drift measurements on 9/26. After this correction, the average for the

TABLE D-2. DAILY CEMS SPAN AND ZERO DRIFT MEASUREMENTS DURING HIGH SULFUR COAL TESTING

	Spray Dryer Inlet								Fabric Filter Outlet							
	DuPont SO2 Monitor				Thermox O2 Monitor				Lear-Siegler				Thermox O2 Monitor			
Date	Zero Value (ppm)	Drift[a] (%)	Span Value (ppm)	Drift[a] (%)	Zero Value (ppm)	Drift[b] (%)	Span Value (ppm)	Drift[b] (%)	Zero Value (ppm)	Drift[c] (%)	Span Value (ppm)	Drift[c] (%)	Zero Value (ppm)	Drift[b] (%)	Span Value (ppm)	Drift [b] (%)
9/2	0	0.0	3050	-3.4	0.5	0.0	21.2	0.3	0.0	0.0	622	0.8	0.7	0.2	20.9	0.0
9/12	4	0.1	3039	-3.8	0.9	0.4	21.5	0.6	-2.5	-0.3	615	0.1	0.8	0.3	20.6	-0.3
9/13	3	0.1	3056	-3.3	0.9	0.4	20.7	-0.2	-2.5	-0.3	628	1.4	0.9	0.4	20.6	-0.3
9/14	3	0.1	3055	-3.3	0.4	-0.1	21.0	0.1					0.9	0.4	20.8	-0.1
9/15	5	0.2	2995	-5.2	0.2	-0.3	20.5	-0.4	0.0	0.0	570	-4.4	1.0	0.5	20.8	-0.1
9/16	1	.0	3030	-4.1	0.3	-0.2	20.9	0.0	-5.0	-0.5	633	1.9	1.0	0.5	20.6	-0.3
9/19	2	0.1	3011	-4.7	0.2	-0.3	21.1	0.2	2.5	0.3	608	-0.6				
9/20	-4	-0.1	3050	-3.4	0.2	-0.3	20.4	-0.5								
9/21	3	0.1	3055	-3.3	0.4	-0.1	20.8	-0.1	0.0	0.0	620	0.6	0.6	0.1	20.6	-0.3
9/22	4	0.1	3033	-4.0	0.2	-0.3	19.6	-1.3	2.5	0.3	625	1.1	1.0	0.5	20.6	-0.3
9/23	0	0.0	3068	-2.9	0.2	-0.3	20.4	-0.5	2.5	0.3	630	1.6	0.8	0.3	20.5	-0.4
9/26	-2	-0.1	2940	-6.9	0.2	-0.3	20.2	-0.7								
9/27	1	.0	3136	-0.8	2.2	1.7	20.9	0.0	2.5	0.3	648	3.4	0.8	0.3	20.5	-0.4
9/28	5	0.2	3138	-0.7	0.3	-0.2	21.0	0.1	2.5	0.3	623	0.9	0.8	0.3	20.5	-0.4
9/29	1	.0	3190	0.9	0.3	-0.2	21.6	0.7	2.5	0.3	623	0.9	0.7	0.2	20.6	-0.3
9/30	5	0.2	3161	.0	0.2	-0.3	20.8	-0.1	2.5	0.3	608	-0.7	0.7	0.2	20.4	-0.5
10/3	3	0.1	3052	-3.4	0.2	-0.3	20.5	-0.4	2.5	0.3	618	0.4	0.7	0.2	20.6	-0.3
10/5	0	0.0	3180	0.6	0.2	-0.3	20.5	-0.4	2.5	0.3	628	1.4			20.6	-0.3
10/6	3	0.1	3194	1.1	0.2	-0.3	20.7	-0.2	2.5	0.3	628	1.4	0.7	0.2	20.7	-0.2
Average	1.9	0.1	3075.4	-2.6	0.4	-0.1	20.8	-0.1	0.9	0.1	620.2	0.6	0.8	0.3	20.6	-0.3
Std. Dev.	2.4	0.1	68.9	2.2	0.5	0.5	0.4	0.4	2.3	0.2	15.9	1.6	0.1	0.1	0.1	0.1
Actual Value	0	-	3161	-	0.5	-	20.9	-	0	-	614	-	0.5	-	20.9	-

[a] Based on full-scale span value of 3200 ppm

[b] Based on full-scale span value of 20.9 percent

[c] Based on full-scale span value of 1000 ppm

remaining seven span drift values improved to -0.3 percent of full scale, with a standard deviation of 0.2 percent.

The inlet Thermox O_2 monitor averaged -0.1 percent O_2 for zero drift, with a standard deviation of 0.5. One value significantly exceeded the control limit of ±0.5 percent O_2 and necessitated immediate instrument repairs. The span drift values also averaged -0.1 percent O_2 but with a slightly lower standard deviation of 0.4. Only two values exceeded the control limt of ±0.5 percent O_2.

At the spray dryer outlet location, the Lear-Siegler SO_2 monitor demonstrated acceptable zero and span drift values. These averaged 0.1 and 0.6 percent of scale, respectively. Only one span drift value exceeded the control limits of ±2.5 percent of full scale. The outlet Thermox O_2 monitor also demonstrated quite acceptable zero and span drift values, averaging 0.3 and -0.3 percent O_2, respectively, with no values exceeding the control limits.

Following span and zero drift checks each day, and subsequent to any span or zero adjustments, a quality control (QC) check gas was introduced to each system at the point of normal span and zero gas entry. The response of the continuous monitor to the QC gas, recorded each day, provides a measure of monitoring data precision in terms of day-to-day variability (i.e., repeatability).

These day-to-day variability data are plotted in Figures D-1 through D-8 in terms of percent recovery. Percent recovery was calculated relative to the certified concentration of the QC gas mixture as:

$$\text{Percent Recovery} = \frac{\text{Instrument Response}}{\text{Tagged QC Gas Conc.}} \times 100 \qquad \text{(D-3)}$$

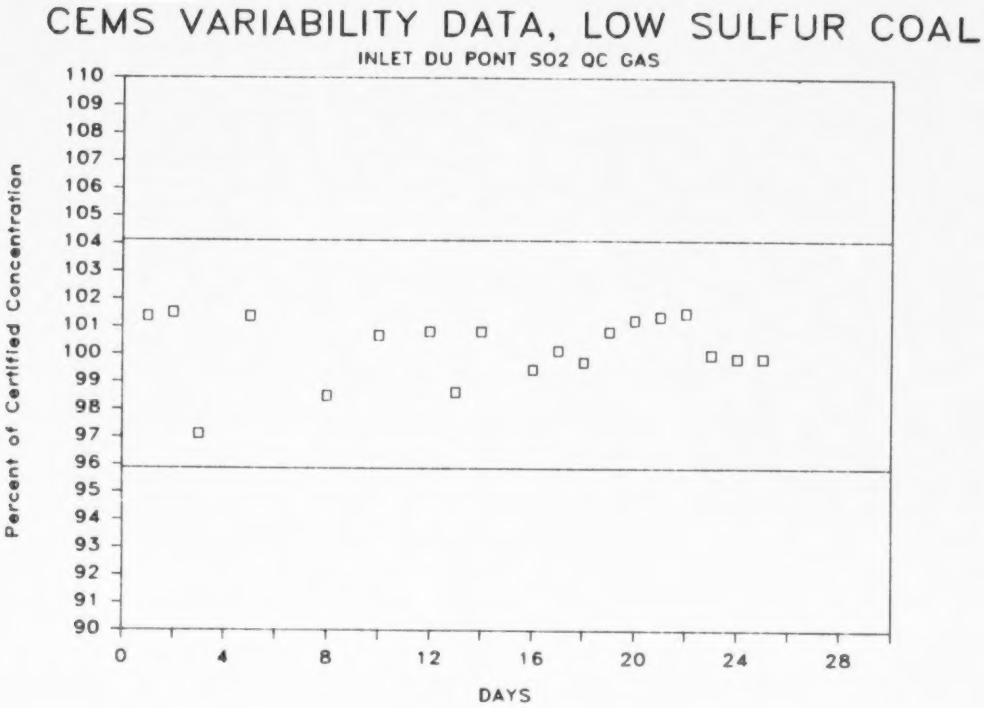

Figure D-1

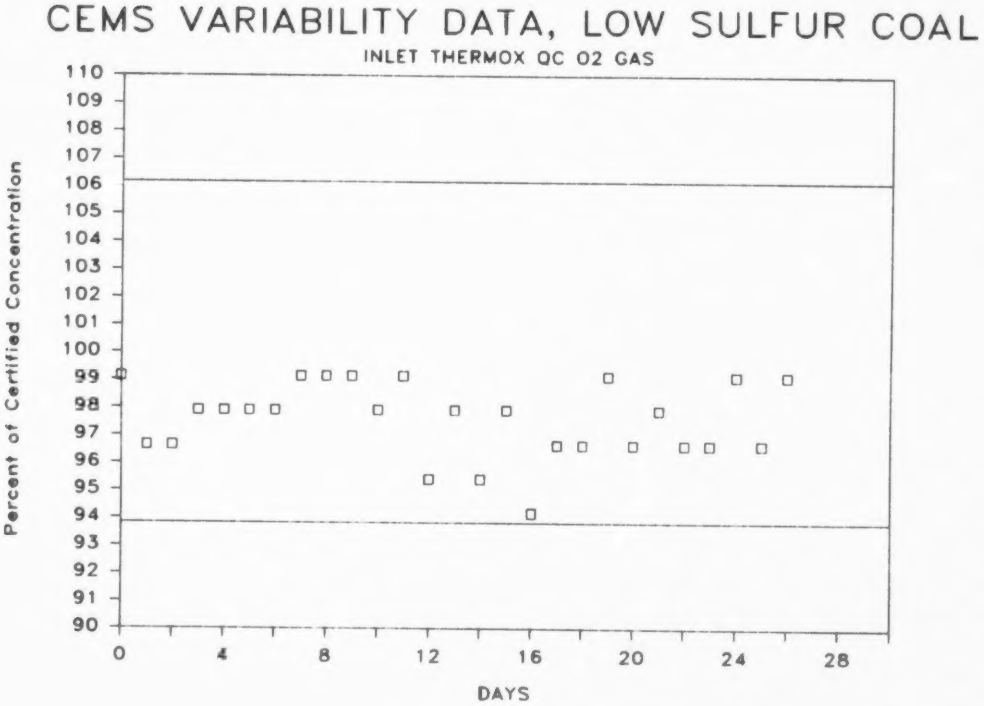

Figure D-2

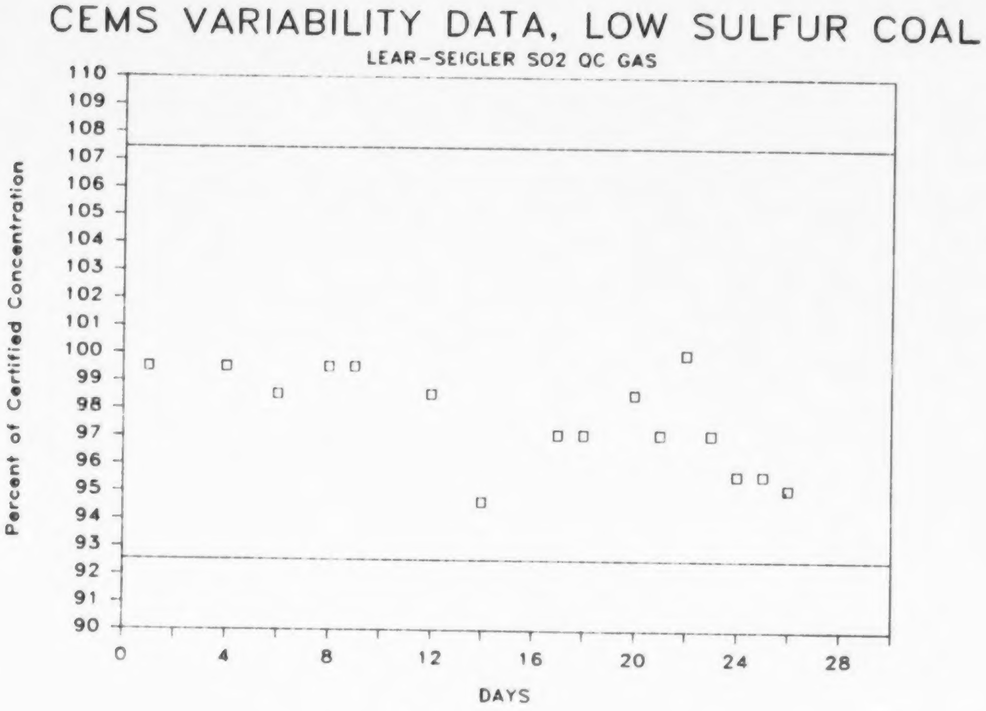

Figure D-3

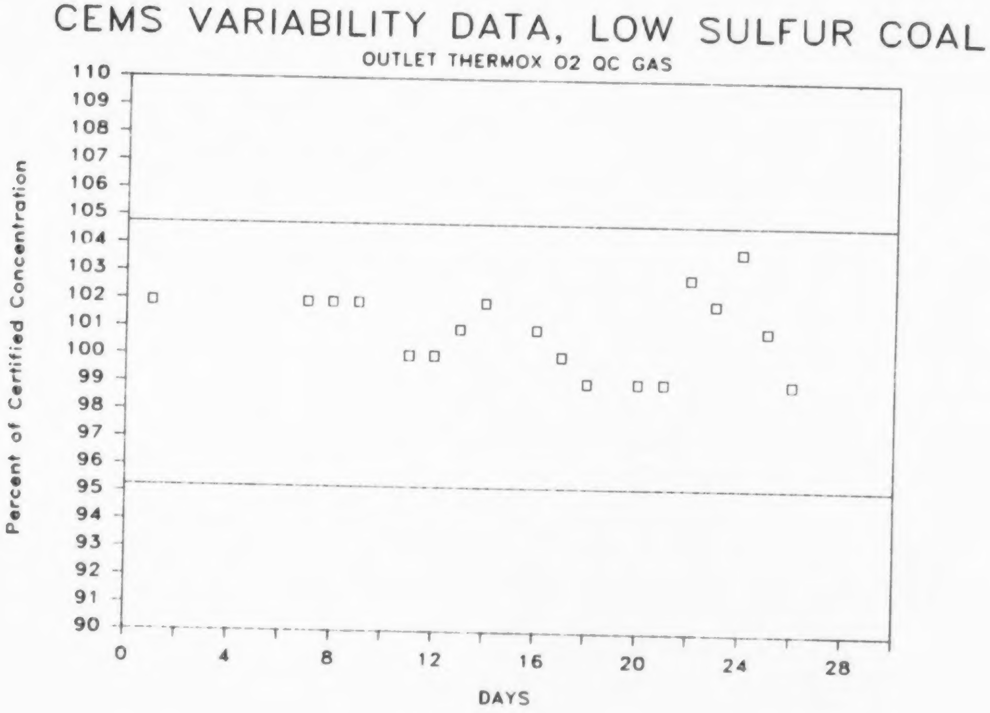

Figure D-4

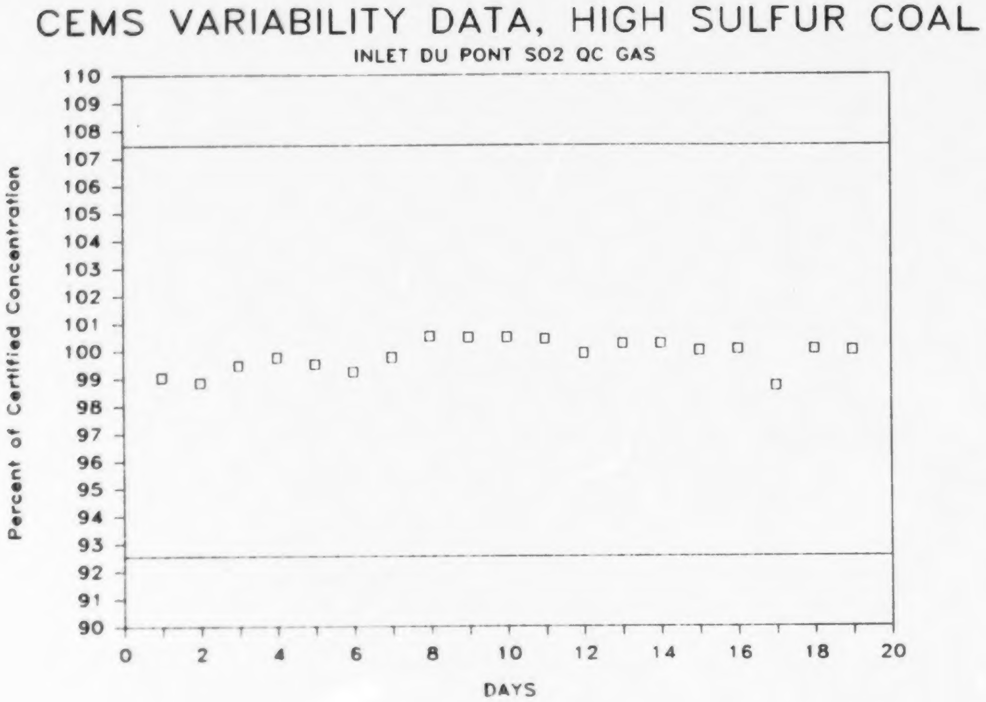

Figure D-5

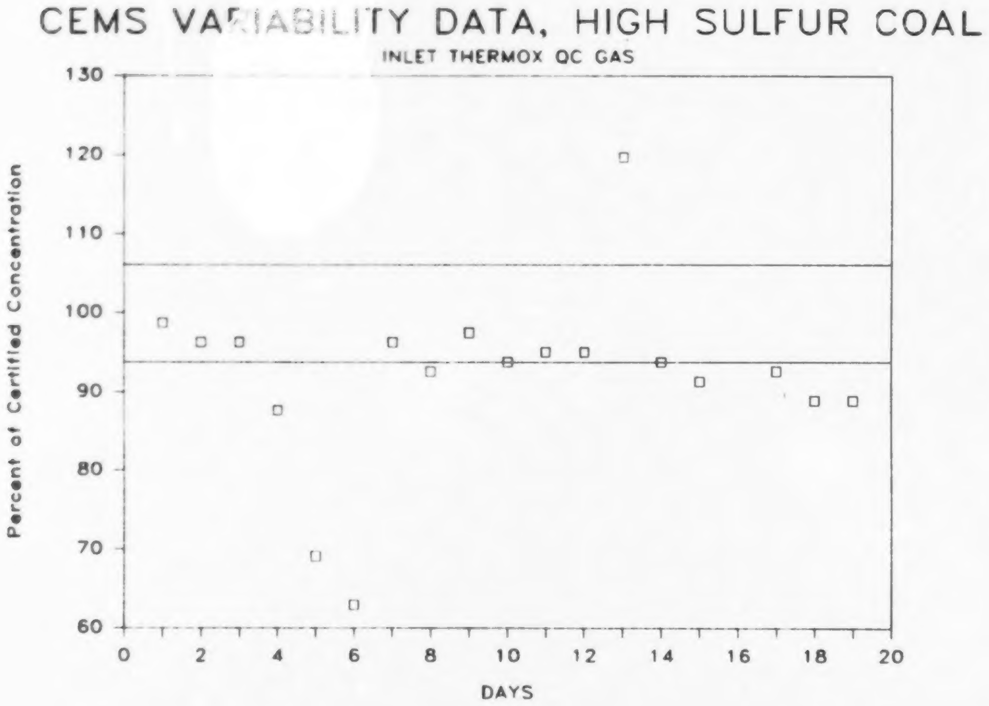

Figure D-6

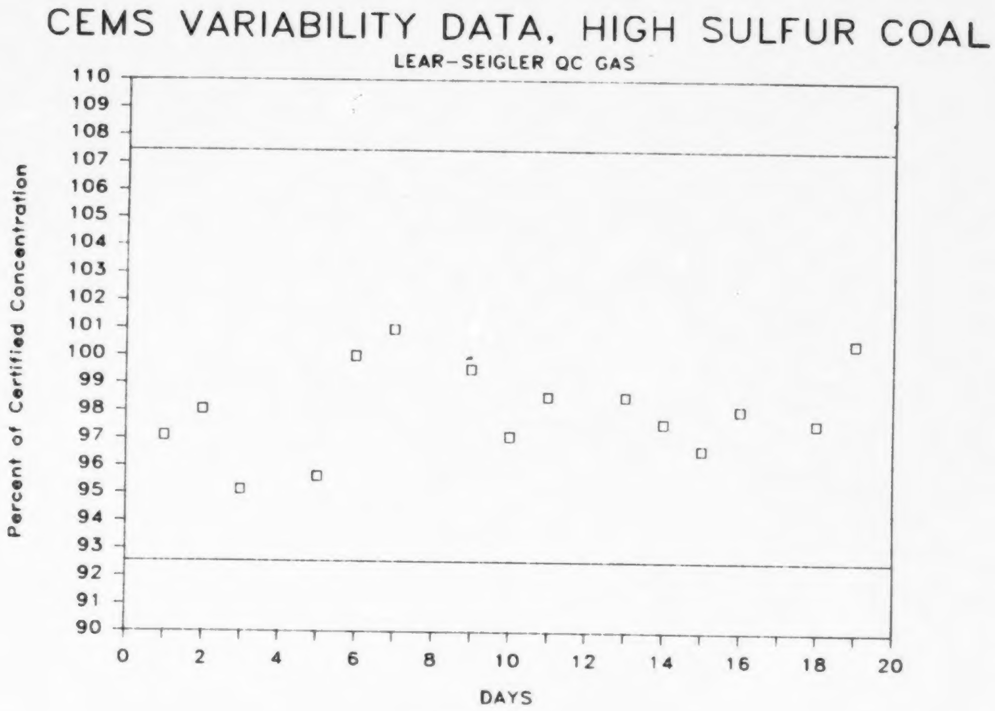

Figure D-7

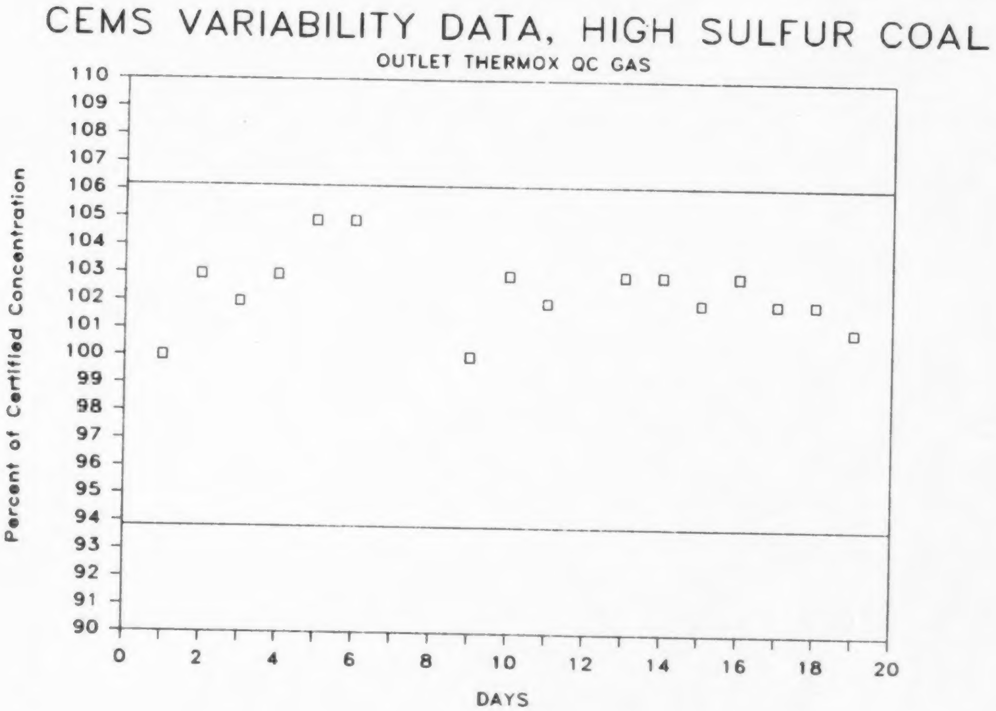

Figure D-8

Also included on the figures are the upper and lower control limits for each monitor. These control limits were calculated as follows:

$$SO_2 \text{ Monit. Cont. Limits} = \frac{\text{Tagged QC Gas Conc.} \quad 2.5\% \text{ of Inst. Span}}{\text{Tagged QC Gas Concentration}} \times 100 \qquad \text{(D-4)}$$

$$O_2 \text{ Monitor Control Limits} = \frac{\text{Tagged QC Gas Conc.} \quad 0.5\% \ O_2}{\text{Tagged QC Gas Concentration}} \times 100 \qquad \text{(D-5)}$$

Figures D-1 through D-4 present QC gas variability data for the low sulfur coal test period for the DuPont inlet SO_2 monitor, the Thermox inlet O_2 monitor, the Lear-Siegler outlet SO_2 monitor, and the Thermox outlet O_2 monitor, respectively. The QC gas concentration data all fall within the control limits as defined above. In Figures D-1 and D-2, the inlet DuPont SO_2 monitor showed recoveries of 97 to 102 percent of a 728 ppm gas, and the inlet Thermox O_2 monitor showed recoveries of 94 to nearly 100 percent of an 8.1 percent O_2 gas. In Figures D-3 and D-4, the Lear-Siegler outlet SO_2 monitor showed percent recoveries of 94 to 100 percent of a 206 ppm gas, and the Thermox outlet O_2 monitor showed 99 to 104 percent recovery of a 10.2 percent O_2 gas.

QC gas variability data for the high sulfur coal test period are plotted in Figures D-5 through D-8. The inlet DuPont SO_2 monitor showed excellent recoveries varying only between 99 and 101 percent of a 2087 ppm gas as seen in Figure D-5. However, Figure D-6 shows that on three days the recovery of the QC gas for the Thermox inlet O_2 monitor was below 90 percent and on a fourth day above 110 percent. These poor recovery values were related to specific maintenance problems with the Thermox O_2 monitor which required immediate attention. These problems tended to limit the usefulness of the CEMS data for these days. Otherwise the QC gas recovery values for this monitor during the high sulfur coal test period varied from 90 to 98 percent. Although several values fell slightly below the lower control limit, this was not the subject of great concern. The QC gas was changed between the low and high sulfur coal periods to a cylinder with a tagged concentration of 8.2 percent O_2. The monitor never measured an O_2 concentration as high as 8.2 percent when this gas was introduced (other than one point where the monitor was malfunctioning). In fact, on several occassions the previous QC gas tagged 8.1 percent O_2 was introduced and measured at a higher O_2 content than the QC gas tagged 8.2 percent O_2. These were not EPA protocol gases, and it was presumed that the tagged analysis was the somewhat higher than the actual gas concentration.

Figure D-7 for the Lear-Siegler SO_2 monitor at the outlet of the fabric filter, for the high sulfur coal test period, showed recoveries of 95 to 101 percent of a 206 ppm gas. All values were within the control limits. Figure D-8, for the outlet Thermox O_2 monitor during the high sulfur coal test period, shows QC gas recoveries of 100 to 105 percent of a 10.2 percent O_2 gas, with all values falling within the control limits.

D.1.2 QC Efforts for Analytical Measurements

As mentioned previously, QC efforts for analytical measurements focused on calcium and sulfate ion concentration analyses. These analyses were considered key to system reagent ratio and lime utilization calculations. The QC efforts included daily analysis of a QC sample, and frequent repeats of calcium and sulfate ion analyses.

The QC sample was a relatively large aliquot of atomizer feed slurry filtrate which had been diluted to avoid subsequent precipitation of limited solubility salts. The results of daily analyses of this QC sample are presented in Figure D-9, for calcium analyses, and Figure D-10, for sulfate analyses. Also plotted in Figures D-9 and D-10 are lines which correspond to the mean values for the calcium and sulfate analyses on the QC sample, respectively, and 95 percent confidence intervals for each set of values.

As can be seen in Figure D-9, the mean calcium concentration value for the QC sample was 5.33 millimoles per liter. The standard deviation for these analyses was 0.10 millimole per liter. This results in a coefficient

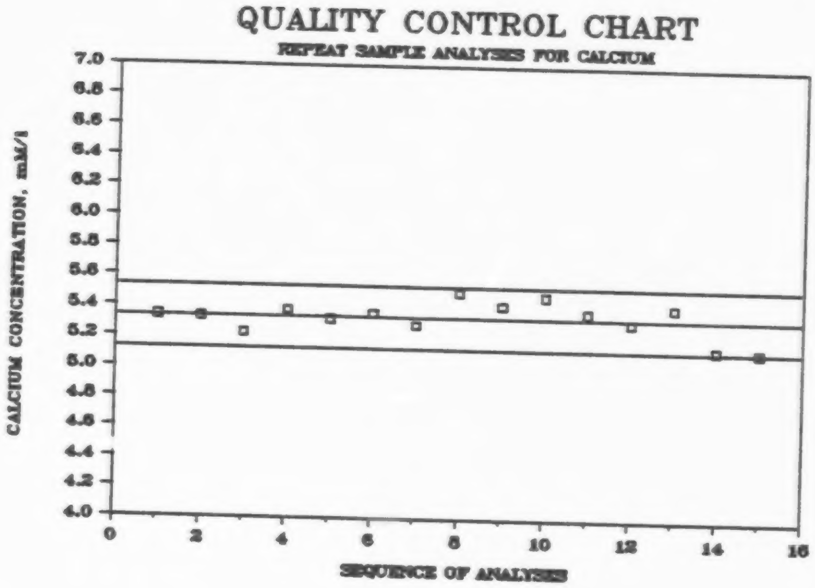

Figure D-9

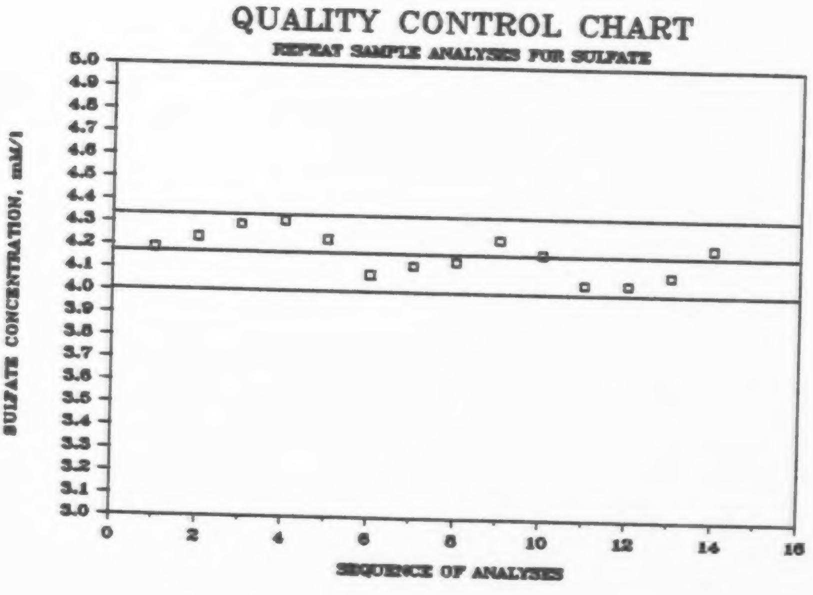

Figure D-10

of variation (CV) of 2.0 percent. The 95 percent confidence intervals depicted in the figure represent approximately ±4 percent of the mean concentration value.

The mean sulfate value for the QC sample, as plotted in Figure D-10, was 4.17 millimoles per liter. The standard deviation of 0.08 milimoles per liter results in a coefficient of variation of 2.0 percent for the sulfate analyses, equal to that of the calcium analyses. Similarly, the 95 percent confidence intervals in Figure D-10 lie at approximately ±4 percent of the mean value.

For the sulfate analyses, a synthetic QC sample was also analyzed frequently. The synthetic sample was quantitatively mixed from sodium sulfate reagent to a desired sulfate ion concentration of 0.44 millimoles/liter. In 19 analyses, the mean concentration value for this QC sample was 0.441 millimoles/liter. The standard deviation of 0.007 millimoles/liter results in a coefficient of variation of 1.7 percent. Although these results are not plotted, the coefficient of variation is very similar to those for the data presented in Figures D-9 and D-10.

A number of repeat or duplicate analyses for calcium and sulfur were conducted on samples which were used to evaluate lime reagent ratio and utilization values. The results of these duplicate analyses are summarized in Tables D-3 and D-4. Listed are the original and duplicate values, the mean of the two values, and the standard deviation and coefficient of variation (i.e., relative standard deviation). Overall precision for the duplicate analyses is expressed in terms of the pooled (i.e., "average") coefficient of variation, CV, calculated as:

$$\text{Pooled CV} = \left(\frac{CV_1^2 + CV_2^2 + \ldots . CV_n^2}{n} \right)^{1/2}$$

where n is the total number of duplicate analyses.

TABLE D-3. CALCIUM DUPLICATE ANALYSES RESULTS

Date	Original (mM/l)	Duplicate (mM/l)	Average (mM/l)	Std Dev (mM/l)	CV (%)
7/29	4.6	4.6	4.6	0.000	0.00
8/12	4.7	5.0	4.9	0.145	2.97
	4.2	4.5	4.3	0.120	2.77
	21.1	21.1	21.1	.000	.00
	12.4	12.4	12.4	0.000	0.00
8/18	4.3	4.4	4.3	0.040	0.93
	5.0	5.2	5.1	0.090	1.78
	8.6	8.9	8.8	0.160	1.83
	4.8	5.0	4.9	0.070	1.43
8/31	4.6	4.7	4.6	0.025	0.54
9/8	12.6	12.4	12.5	0.095	0.76
	4.2	4.2	4.2	0.015	0.36
9/9	29.7	30.4	30.0	0.335	1.12
	3.1	3.1	3.1	.000	.00
12/7	12.7	12.2	12.5	0.250	2.01
	5.1	5.3	5.2	0.075	1.44
	Pooled Coefficient of Variation				1.46

TABLE D-4. SULFATE DUPLICATE ANALYSES RESULTS

Date		Original (mM/l)	Duplicate (mM/l)	Average (mM/l)	Std Dev (mM/l)	CV (%)
8/1		16.6	16.5	16.6	0.075	0.45
8/4		15.1	14.8	14.9	0.160	1.07
		39.2	39.2	39.2	0.000	0.00
8/11		2.0	2.0	2.0	0.017	0.82
		1.9	1.9	1.9	0.008	0.41
8/16		30.6	30.5	30.5	0.046	0.15
		3.8	4.0	3.9	0.082	2.11
8/19		1.9	1.9	1.9	0.017	0.90
8/26		2.2	2.2	2.2	0.010	0.46
		3.8	3.8	3.8	0.021	0.55
8/31		1.7	1.7	1.7	0.020	1.18
		3.0	3.0	3.0	.000	.00
		2.0	2.0	2.0	0.000	0.00
		2.3	2.3	2.3	0.015	0.66
		2.3	2.3	2.3	0.010	0.44
		22.2	22.2	22.2	.000	.00
10/18	(SYS 1)	67.1	66.8	66.9	0.140	0.21
		88.9	89.2	89.0	0.125	0.14
10/18	(SYS 2)	4.5	4.5	4.5	0.020	0.45
		82.3	82.3	82.3	.000	.00
12/5		252.4	251.4	251.9	0.500	0.20
		13.0	13.0	13.0	.000	.00
12/12		331.7	331.7	331.7	.000	.00
		301.2	306.1	303.7	2.450	0.81
		Pooled Coefficient of Variation				0.676

The pooled CV for the duplicate analyses is a measure of within-day analytical precision, or replicability. Ten percent is typically considered to be an acceptable level of precision for replicate analyses, while a CV of five percent or less is considered to be very good. The pooled CV values in Tables D-3 and D-4 of less than 2 percent for the calcium duplicates and less than 1 percent for the sulfate analyses indicate excellent precision in these analyses.

D.2 QA AUDIT RESULTS

The previous subsection presented QC data collected during this program which pertained to precision of the measurement data. The internal QC procedures upon which these data are based represented one part of the overall quality assurance (QA) effort for this test program. As another part of this QA effort, the project QA coordinator spent Wednesday through Friday, August 10-12, 1983, conducting a QA audit on site. Audit activities included performance audits of the continuous emissions monitors, on-site chemical analyses, balances, and dry gas meters, as well as a systems audit of the overall test effort. The internal QC procedures described in the previous subsection provided the mechanism for day-to-day control and assessment of data quality, with emphasis upon precision. The QA audit, on the other hand, provided an independent, point-in-time assessment of data quality and adequacy of the internal QC system. The performance audit focused upon assessing accuracy of the measurement data by challenging the various measurement systems with reference standards, while the systems audit emphasized review of procedures and protocols.

Performance audit results are summarized in Table D-5. Measured error values are presented for each parameter, along with the audit standards used, instrument identifications, and measurement methods. As indicated in the table, results were excellent for all parameters, falling well within the accuracy objectives specified in the Quality Assurance Project Plan. The systems audit indicated generally careful attention to procedural

TABLE D-5. SUMMARY OF PERFORMANCE AUDIT RESULTS

Parameter	Analytical Method	Instrument	Audit Standard(s)	Error[a]
SO_2 (Spray Dryer Inlet)	CEM	Du Pont 400/460 S/N 4723	EPA SO_2/N_2 Cyl. #FF 1839 & FF 6409	0.0% (0 ppm), -0.8% (-4 ppm) (n=2)
SO_2 (Spray Dryer Outlet)	CEM	Du Pont 400/460 S/N 4723	EPA SO_2/N_2 Cyl. #FF 1839 & FF 6409	7.9% (12 ppm), 0.9% (5 ppm) (n=2)
SO_2 (Baghouse Outlet)	CEM	Lear Siegler SM 810 S/N 79297M	EPA SO_2/N_2 Cyl. #FF 1829 & FF 6409	-2.0% (-3 ppm), -2.3% (-12 ppm) (n=2)
O_2 (Spray Dryer Inlet)	CEM	Thermox WDG EPA #072936	EPA O_2/N_2 Cyl. #FF 7381	4.6% (0.37% O_2) (n=1)
O_2 (Spray Dryer Outlet)	CEM	Thermox WDG EPA #072936	EPA O_2/N_2 Cyl. #FF 7381	2.1% (0.17% O_2) (n=1)
O_2 (Baghouse Outlet)	CEM	Thermox WDG EPA #072941	EPA O_2/N_2 Cyl. #FF 7381	4.6% (0.37% O_2) (n=1)
O_2	EPA Method 3	Orsat	Scott Envir. Technology $CO_2/O_2/N_2$ Cyl. #AAL 6516	-1.1% (-0.11% O_2), -0.6% (-0.06% O_2) (n=2)
CO_2	EPA Method 3	Orsat	Scott Envir. Technology $CO_2/O_2/N_2$ Cyl. #AAL 6516	4.5% (0.09% CO_2), -0.5% (0.01% CO_2) (n=2)
Mass	Balance	Mettler H80 S/N 832103	Class S Weights 4254-S S/N 3697	≤±3.3% (0.0002 g ±0.0002 g)
		Mettler H45AR S/N 798793	Class S Weights 4254-S S/N 3697	≤±0.4% (-0.00004 g ±0.00007 g)
		Cahn 21	Class S Weights 4254-S S/N 3697	≤±0.7% (0.00012 g ±0.00012 g)
Gas Volume	Dry Gas Meter	LSI PM 100 #D348	Standard DGM #598940	0.64% ±0.90% (n=3)
		LSI PM 100 #E342	Standard DGM #598940	0.33% ±0.68% (n=3)
		LSI PM 100 #D314	Standard DGM #598940	-0.01% ±0.88% (n=3)
SO_2 (Sampling and Analysis)	EPA Method 6 (Combined with Method 5 or 17)	---	Scott Envir. Technology EPA Traceability Protocol SO_2/N_2 Cyl. #AAL 11470	0.4% (2.5 ppm) (n=1)
SO_4 (Analysis Only)	Ion Chromatography	Dionex	EPA QA Reference Samples Lot #0980	1.44% ±1.39% (n=12)
Solid Calcium	Atomic Adsorption	AA	NBS SRM #1c NBS SRM #88a	-7.3% (-2.2 wt.%), -2.4% (-1.2 wt.%) (n=2)
Temperature (ASTM Temperature Rise)	Dial Thermometer	---	Mercury Thermometer ASTM Type 64F S/N 582809	0.1° to 0.4°C (n=3)

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[a] Both relative and absolute error values are presented. Absolute error is shown in parentheses. Where 3 or more tests were performed (i.e., n ≥ 3), the mean and 95% confidence interval are indicated.

details and quality control efforts. Detailed results and audit procedures are discussed below.

D.2.1 Continuous Emission Monitors

The continuous emission monitoring (CEM) system, consisting of a Lear-Siegler SO_2 monitor, a DuPont SO_2 monitor, and two Thermox O_2 monitors was audited by challenging each monitor with EPA audit gas mixtures. The three extractive monitors (the DuPont and Thermoxes) were audited by introducing the audit gas mixtures upstream of the sampling lines so as to check the complete sampling system. For the DuPont and the Thermox common to both spray dryer inlet and outlet, audit gases were introduced through both sample lines. For the Lear-Siegler, which is an in-situ monitor, the audit gas was introduced to the gas cell in the same manner as the QC gas mixture. Detailed results for SO_2 monitor performance at each of the three sampling locations are presented in Table D-6. Table D-7 presents corresponding data for the O_2 monitors. Results are expressed both in terms of absolute error and relative error. Absolute error represents the difference between measured and input concentrations expressed in terms of the measurements units (i.e., ppm SO_2 and % O_2). Relative error reflects this same difference expressed as a percentage of the input concentration.

D.2.2 Method 6 SO_2 Determinations

The performance audit of Method 6 SO_2 measurements addressed the measurements as a whole, including both sample collection and analysis, as well as the analytical portion of the method alone. The analytical portion of the audit primarily addressed the ion chromatographic method used for the Method 6 analyses.

For the audit of both sampling and analysis, a combined Methods 6 and 17 sampling train was used to collect a sample of an SO_2/N_2 gas mixture. A typical sample probe, complete with in-stack filter assembly, was used to withdraw the gas sample from a manifold system which incorporated a tee

TABLE D-6. SO_2 MONITOR AUDIT RESULTS

Input Concentration (ppm)	Spray Dryer Inlet			Spray Dryer Outlet			Baghouse Outlet		
	Measured Concentration (ppm)	Absolute Error (ppm)	Relative Error[a] (%)	Measured Concentration (ppm)	Absolute Error (ppm)	Relative Error[a] (%)	Measured Concentration (ppm)	Absolute Error (ppm)	Relative Error[a] (%)
151	151	0	0.0	163	12	+7.9	148	-3	-2.0
530	526	-4	-0.8	535	5	+0.9	518	-12	-2.3

[a] Relative Error = $\frac{\text{Measured Conc. - Input Conc.}}{\text{Input Conc.}} \times 100$

TABLE D-7. O_2 MONITOR AUDIT RESULTS

Input Concentration (% O_2)	Spray Dryer Inlet			Spray Dryer Outlet			Baghouse Outlet		
	Measured Concentration (% O_2)	Absolute Error (% O_2)	Relative Error[a] (%)	Measured Concentration (% O_2)	Absolute Error (% O_2)	Relative Error[a] (%)	Measured Concentration (% O_2)	Absolute Error (% O_2)	Relative Error[a] (%)
8.13	8.5	0.37	+4.6	8.3	0.17	+2.1	8.5	0.37	+4.6

[a] Relative Error = $\frac{\text{Measured Conc. - Input Conc.}}{\text{Input Conc.}} \times 100$

arrangement to maintain atmospheric pressure at the manifold. The audit gas was an EPA Traceability Protocol mixture (612.6 ppm SO_2) obtained from Scott Environmental Technology, Inc. Two test runs were performed, but the validity of the results for the first run is questionable since a small (but unknown) amount of gas was inadvertently introduced into the sample train before the initial dry gas meter (DGM) reading was taken. The measured concentration for this first test was 636 ppm, for a relative error of 3.8%. Results for the second test were significantly better, with a measured concentration of 615.2 ppm and corresponding relative error of 0.4%.

Although it is likely that at least part of the error observed for the first test above was due to the QA Coordinator error in introducing audit gas too soon, data for the analytical audit indicate a probability of about 15% that an error of this magnitude might occur due to analytical variability (imprecision) alone. The anaytical audit consisted of submitting two sets of EPA Method 6 audit samples for analysis. These were dilute H_2SO_4 solutions contained in glass ampules. Both sets were analyzed by ion chromatography, one set in duplicate. Also, the two sets represented five duplicate sample pairs. Thus, the audit data may be used to evaluate precision as well as accuracy of the analytical data.

Audit results, in terms of analytical accuracy, are presented in Table D-8. The 95% confidence interval for mean relative error (i.e., systematic error or bias) is the interval ranging from 0.1% to 2.8%. Since this interval does not include 0%, a slight bias is indicated. Using these same data, a statistical tolerance limit was calculated for the Method 6 analyses. This tolerance limit indicates a 95% probability that at least 90% of the analytical results would have a total error (i.e., systematic error plus random error) between -4.1% and 6.9%.

As mentioned above, since the audit included both duplicate samples and duplicate analyses, a rather detailed evaluation of anlaytical precision is possible. Table D-9 summarizes the precision data for Method 6 sampling and analysis, in terms of coefficient of variation (i.e., the standard deviation

TABLE D-8. AUDIT RESULTS FOR DIONEX SO_2 (AS $SO_4^=$) ANALYSES

Sample ID	Actual Conc. (mg/Nm^3)	Measured Conc. (mg/Nm^3)	Absolute Error (mg/Nm^3)	Relative Error (%)
5504	2287.8	2272.3	-15.5	-0.68
5802	2287.8	2299.6	11.8	0.51
2331	1906.5	1910.8	4.3	0.22
2166	1906.5	1927.8	17.0	1.11
4014	762.6	774.2	11.6	1.52
4077	762.6	764.6	2.0	0.26
8081	381.3	384.2	2.9	0.76
8257	381.3	390.9	9.6	2.51
1943	1143.9	1216.2	72.3	6.32[b]
1740	1143.9	1165.0	21.1	1.84
		Mean Relative Error (95% C.I.)		1.44 ±1.39 0.89 ±0.74[c]

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[a] $\text{Relative Error} = \frac{\text{Measured Conc.} - \text{Actual Conc.}}{\text{Actual Conc.}} \times 100$

[b] Outlier based on Dixon criteria applied at 0.05 significance (i.e., 95% confidence)

[c] Mean relative error calculated omitting results for Sample #1943

TABLE D-9. PRECISION OF METHOD 6 DATA

Sample ID	Source of Variability (Imprecision): Sample Analysis CV[a] (%)	Sample Preparation Plus Analysis CV[a] (%)	Sample Collection Plus Preparation Plus Analysis CV[a] (%)
5	0.59	0.84	
2	0.93	0.63	
4	1.16	0.88	
8	0.51	1.22	
1	0.78	3.04	
6			2.37
Pooled CV[b]	0.83	1.59	2.37
Percentage of Total Variability	12.3	45.0	100.0
Percentage by Component	12.3 (Analytical)	32.7 (Sample Prep)	55.0 (Sample Collection)

[a] Coefficient of variation, where $CV = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$

[b] "Average" coefficient of variation

expressed as a percentage of the mean) for replicate test runs. The relative contribution of each of the three major components of variability to total variabiity (imprecision) is also shown. The analytical component was calculated based on results for duplicate analyses. The sample preparation component is based on results for duplicate samples analyzed at different times and includes variability due to sample dilution, instrument calibration, etc. The sample collection component is based on the two sampling test runs discussed above.

D.2.3 Calcium Analyses

The performance audit of calcium analyses for solid samplis consisted of submitting two limestone audit samples for analyses. The audit samples were Standard Reference Materials (SRMs), 88a, dolomitic limestone, and 1c, argillaceous limestone, obtained from the National Bureau of Standards (NBS). Audit results are presented in Table D-10.

D.2.4 Orsat Analyses

The performance audit for Method 3 analyses of O_2 and CO_2 consisted of submitting duplicate bag samples of a standard gas mixture for analysis. The audit gas mixture was a certified standard obtained from Scott Environmental Technology, Inc., containing 9.96% O_2 and 2.01% CO_2. Both bags were analyzed in duplicate, and results for both parameters were within ±0.2% absolute. Audit results are presented in Table D-11.

D.2.5 Dry Gas Meters

Each of three dry gas meters (i.e., sampling consoles) used for gas and particulate sampling were audited by comparision to a standard dry gas meter which had been calibrated independently of the test meters. Triplicate audit runs were performed on each meter. Test data were used to calculate mean correction factors and corresponding 95% confidence intervals for each meter. These values were than compared to the correction factors obtained

TABLE D-10. CALCIUM AUDIT RESULTS

Sample ID	Actual Concentration (Wt % CaO)	Measured Concentration (Wt % CaO)	Absolute Error (Wt % CaO)	Relative Error[a] (%)
1c	50.3	49.	-1.2	-2.4
88a	30.1	27.9	-2.2	-7.3

[a] Relative Error = $\frac{\text{Measured Conc. - Actual Conc.}}{\text{Actual Conc.}} \times 100$

TABLE D-11. ORSAT AUDIT RESULTS

		Sample A		Sample B	
Parameter	Actual Concentration	Measured Concentration	Absolute Error	Measured Concentration	Absolute Error
O_2	9.96%	9.85%	-0.11%	9.90%	-0.06%
CO_2	2.01%	2.10%	0.09%	2.00%	-0.01%

for the pretest meter calibrations. As indicated in Table D-12, pretest calibration correction factors for all three meters fell within the 95% confidence interval for the mean measured (i.e., audit) correction factors. Mean relative errors for all three meters were less than 1%.

D.2.6 Balances

The three analytical balances (two Radian balances and one Niro balance) were audited using a set of Class S reference weights. Results are presented in Table D-13.

D.2.7 ASTM Temperature Rise

The performance audit of the ASTM temperature rise tests consisted of a check of the accuracy of the dial thermometer used in this procedure. The thermometer was compared with a high precision ASTM Type 64F mercury thermometer. Over a temperature range of 27°F to 53°C, the dial thermometer was accurate to ±0.5%°C. Audit results are presented in Table D-14.

D.2.8 Systems Audit

The systems audit consisted of the review and evaluation of calibration documentation, data forms, analytical notebooks, sample logging and custody procedures, data reduction and validation procedures, and general compliance with the prescribed system of internal quality control. Although some analytical operations were observed (Orsat analyses, Dionex analyses, and ASTM temperature rise tests), as were calibration and QC checks associated with the CEM system, observation of sampling operations was limited to preparatory activities. No sampling was performed during the audit period due to problems with spray dryer system operations. Overall, based on observations and review of sampling and analytical documentation, the systems audit revealed generally acceptable procedures and techniques, with no major deficiencies in any particular area. Attention to details of the

TABLE D-12. DRY GAS METER (DGM) AUDIT RESULTS

Console ID	DGM Correction Factor, Y, from Pretest Calibration	Measured DGM Correction Factors (Audit Results)[a]			Mean Measured DGMCF (95% C.I.)[b]	Mean Relative Error, % (95% C.I.)[c]
		Run 1	Run 2	Run 3		
LSI PM 100 #D348	1.0011	0.9926	0.9989	0.9927	0.9947 ±0.0090	0.64 ±0.90
LSI PM 100 #E342	1.0149	1.0113	0.0145	1.0090	1.0116 ±0.0068	0.33 ±0.68
LSI PM 100 #D314	1.0008	0.9978	1.0048	1.0001	1.0009 ±0.0088	-0.01 ±0.88

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[a] $$Y_i = \frac{V_{STD} \; P_b \; (T_{Test} + 460)}{V_{Test} \; (P_b + \frac{\Delta H}{13.6})(T_{STD} + 460)}$$

[b] Average dry gas meter correction factor (DGMCF) based on audit results; 95% confidence interval (C.I.) for the mean reflects variability about the mean for the three test runs.

[c] Audit results expressed in terms of average percentage error, where

$$\text{Relative Error} = \frac{\text{Pretest DGMCF} - \text{Mean Measured DGMCF}}{\text{Mean Measured DGMCF}} \times 100$$

TABLE D-13. ANALYTICAL BALANCE AUDIT DATA

	Mettler H45AR S/N 798793		Mettler H80 S/N 832103		CAHN 21	
Standard Weight (g)	Observed Weight (g)	Absolute Error (g)	Observed Weight (g)	Absolute Error (g)	Observed Weight (g)	Absolute Error (g)
100.00000	99.99958	-0.00042				
50.00000	49.99975	-0.00025				
30.00000	29.99991	-0.00009				
10.00000	9.99998	-0.00002				
5.00000	5.00000	0.00000	5.0003	0.0003		
3.00000	3.00017	0.00017	3.0002	0.0002		
2.00000	2.00008	0.00008	2.0000	0.0000		
1.00000	1.00000	0.00000	1.0000	0.0000		
0.50000	0.50000	0.00000	0.5009	0.0009		
0.30000	0.30008	0.00008	0.3007	0.0007		
0.20000	0.20005	0.00005	0.2003	0.0003	0.20046	0.00046
0.10000	0.10000	0.00000	0.1001	0.0001	0.10019	0.00019
0.05000	0.04983	-0.00017	0.0500	0.0000	0.05010	0.00010
0.03000	0.02993	-0.00007	0.0298	-0.0002	0.03009	0.00009
0.02000	0.01998	-0.00002	0.0197	-0.0003	0.02004	0.00004
0.00500	0.00500	0.00000	0.0050	0.0000	0.00502	0.00002
0.00300	0.00300	0.00000	0.0029	-0.0001	0.00302	0.00002
0.00200	0.00200	0.00000	0.0020	0.0000	0.00201	0.00001
Error Range (g)	-0.00042-0.00017		-0.0003-0.0009		0.00001-0.00046	
Mean Error (g) (±95% C.I.)	-0.00004 ±0.00007		0.0002 ±0.0002		0.00012 ±0.00012	

TABLE D-14. ASTM TEMPERATURE RISE THERMOMETER AUDIT

Standard Temperature (°C)	Observed Temperature (°C)	Absolute Error (°C)	Relative Error[a] (%)
27.4	27.0	0.4	-1.5
44.7	44.5	0.2	-0.4
53.4	53.5	0.1	-0.2

[a] Relative Error = $\frac{\text{Observed Temp.} - \text{Actual Temp.}}{\text{Actual Temp.}} \times 100$

rather extensive internal QC system was described by the QA coordinator as being especially commendable.

APPENDIX E

ADDITIONAL WASTE SOLIDS CHARACTERIZATION ANALYSES

TABLE E-1. RIVERSIDE LOW SULFUR COAL ELEMENTAL ANALYSIS[a] OF SPRAY DRYER WASTE PRODUCT

		Neutral Extract[b]		EP Extract[c]	
	Solid Sample (μg/g)	Uncured (mg/L)	Cured (mg/L)	Uncured (mg/L)	Cured (mg/L)
Aluminum	53,000[d]	2.7	0.60	<0.05[e]	1.7
Antimony	<20	<0.03	<0.03	<0.03	<0.03
Arsenic[f]	<20	<0.003	<0.003	<0.003	<0.003
Barium	2,900	1.3	0.24	1.2	1.2
Beryllium	0.94	0.001	<0.0005	<0.0005	0.002
Boron	ND[g]	1.1	0.009	13	0.073
Cadmium[f]	<1	<0.0005	<0.0005	<0.0005	<0.0005
Calcium	160,000	760	120	2,500	790
Chromium	69	0.28	0.11	<0.001	<0.006
Cobalt	8.9	0.021	<0.006	<0.006	0.002
Copper	33	0.054	<0.001	<0.001	0.095
Iron	23,000	0.020	<0.008	<0.008	0.014
Lead[f]	31	<0.002	<0.002	<0.002	<0.002
Magnesium	14,000	1.3	1.2	230	27
Manganese	638	0.006	<0.001	8.6	0.73
Mercury[f]	ND[g]	<0.0002	<0.0002	<0.0002	<0.0002
Molybdenum	24	0.56	0.11	0.67	0.21
Nickel	200	0.019	<0.003	0.95	0.076
Potassium	7,900	2.7	1.2	6.0	3.8
Selenium[f]	<30	<0.003	<0.003	<0.003	<0.003
Silicon	99,000	5.3	0.83	15	11
Silver	<0.4	<0.002	<0.002	<0.002	<0.002
Sodium	3,400	25	20	36	33
Strontium	2,000	13	2.2	25	8.5
Thallium	<30	<0.09	<0.09	<0.09	<0.09
Tin	<100	<0.1	<0.1	<0.1	<0.1
Titanium	2,900	0.092	<0.005	<0.005	0.009
Vanadium	480	0.90	0.14	0.28	0.19
Zinc	28	0.008	0.004	0.014	0.010

[a] Concentrations measured using inductively coupled argom plasma emission spectrometry (ICPES) unless otherwise noted.

[b] Neutral extract obtained using EPA extraction procedure, but without acetic acid addition.

[c] EP extraction procedure described in Federal Register 45(98) 33127, May 19, 1980.

[d] Analysis was by ICPES on solution prepared by lithium metaborate fusion. Other elemental concentrations in solids were determined using perchloric acid solutions.

[e] "Less than" values indicate analytical detection limit.

[f] Concentrations in extracts measured by atomic absorption spectrophotometry.

[g] Not determined because boron and mercury are lost during digestion procedure.

TABLE E-2. RIVERSIDE HIGH SULFUR COAL ELEMENTAL ANALYSIS[a] OF SPRAY DRYER WASTE PRODUCT

	Solid Sample	Neutral Extract[b]		EP Extract[c]		
	(μg/g)	Uncured (mg/L)	Cured (mg/L)	Uncured (mg/L)	Uncured (mg/L)	Cured (mg/L)
Aluminum	33,000[d]	0.59	0.087	<0.05[e]	<0.05	4.3
Antimony	<30	<0.03	<0.03	<0.03	<0.03	<0.03
Arsenic[f]	<20	<0.003	<0.003	<0.003	<0.003	<0.003
Barium	260	0.82	0.89	1.6	1.6	0.99
Beryllium	1.7	0.001	<0.0005	<0.0005	0.002	<0.0005
Boron	ND[g]	5.7	<0.009	7.4	6.4	6.2
Cadmium[f]	<1	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Calcium	200,000	1,100	550	2,900	2,800	3,000
Chromium	54	0.20	0.14	0.15	0.14	0.039
Cobalt	15	0.025	<0.006	<0.006	<0.006	<0.006
Copper	45	0.084	<0.001	<0.001	<0.001	<0.001
Iron	39,000	0.008	<0.008	<0.008	<0.008	<0.06
Lead[f]	48	<0.002	<0.002	<0.002	<0.002	<0.002
Magnesium	4,600	0.50	<0.03	0.11	0.054	21
Manganese	190	0.005	<0.001	<0.001	<0.001	0.65
Mercury[f]	ND[g]	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Molybdenum	29	0.55	0.36	0.60	0.55	0.36
Nickel	50	0.023	<0.003	<0.003	<0.003	0.010
Potassium	8,700	4.9	12	2.9	2.7	11
Selenium[f]	<50	<0.003	<0.003	<0.003	<0.003	<0.003
Silicon	70,000	0.55	0.56	1.5	1.6	21
Silver	<2	<0.002	<0.002	<0.002	<0.002	<0.002
Sodium	1,040	8.9	14	9.3	8.9	16
Strontium	170	0.62	0.77	<0.004	<0.004	0.56
Thallium	<30	<0.09	<0.09	<0.09	<0.09	<0.09
Tin	<100	<0.1	<0.1	<0.1	<0.1	<0.1
Titanium	2,400	0.082	<0.005	<0.005	<0.005	<0.005
Vanadium	99	0.068	<0.003	<0.003	<0.003	<0.003
Zinc	210	0.017	0.005	0.005	0.005	0.093

[a] Concentrations measured using inductively coupled argon plasma emission spectrometry (ICPES) unless otherwise noted.

[b] Neutral extract obtained using EPA extraction procedure, but without acetic acid addition.

[c] EP extraction procedure described in Federal Register 45(98) 33127, May 19, 1980.

[d] Analysis was by ICPES on solution prepared by lithium metaborate fusion. Other elemental concentrations in solids were determined using perchloric acid solutions.

[e] "Less than" values indicate analytical detection limit.

[f] Concentrations in extracts measured by atomic absorption spectrophotometry.

[g] Not determined because boron and mercury are lost during digestion procedure.

TABLE E-3. RIVERSIDE HIGH SULFUR COAL ELEMENTAL ANALYSIS OF[a] SPRAY DRYER WASTE PRODUCT, FOR TEST WITH $CaCl_2$ ADDITION

	Solid Sample (μg/g)	Neutral Extract[b] Uncured (mg/L)	Neutral Extract[b] Cured (mg/L)	EP Extract[c] Uncured (mg/L)	EP Extract[c] Cured (mg/L)
Aluminum	35,000[d]	0.26	0.16	8.0	7.5
Antimony	<6[e]	<0.03	<0.03	<0.03	<0.03
Arsenic[f]	<11	<0.003	<0.003	<0.003	<0.003
Barium	210	0.45	0.31	1.5	0.93
Beryllium	1.5	<0.0005	<0.0005	0.005	0.002
Boron	ND[g]	7.5	<0.009	25	12
Cadmium[f]	6.1	<0.0005	<0.0005	<0.0005	<0.0005
Calcium	180,000	900	260	3,000	2,000
Chromium	49	0.17	0.12	0.13	0.055
Cobalt	14	<0.006	0.006	<0.006	<0.006
Copper	1.1	0.018	0.018	0.007	0.010
Iron	45,000	<0.008	<0.008	1.8	0.34
Lead[f]	22	<0.002	<0.002	<0.002	<0.002
Magnesium	4,500	0.15	0.80	100	48
Manganese	200	<0.001	0.004	4.1	1.8
Mercury[f]	ND[g]	<0.0002	<0.0002	<0.0002	<0.0002
Molybdenum	27	0.65	0.28	0.72	0.30
Nickel	50	<0.003	0.004	0.13	0.050
Potassium	9,300	16	26	19	26
Selenium[f]	<20	<0.003	<0.003	<0.003	<0.003
Silicon	78,000	2.7	6.1	49	45
Silver	<0.4	<0.002	<0.002	<0.002	<0.002
Sodium	3,200	18	22	25	24
Strontium	240	1.8	1.6	3.3	2.3
Thallium	<20	<0.09	<0.09	<0.09	<0.09
Tin	<20	<0.1	<0.1	<0.1	<0.1
Titanium	2,500	<0.005	0.032	<0.005	<0.005
Vanadium	86	<0.003	0.12	0.006	<0.003
Zinc	220	0.007	0.004	0.36	0.27

[a] Concentrations measured using inductively coupled argon plasma emission spectrometry (ICPES) unless otherwise noted.

[b] Neutral extract obtained using EPA extraction procedure, but without acetic acid addition.

[c] EP extraction procedure described in Federal Register 45(98) 33127, May 19, 1980.

[d] Analysis was by ICPES on solution prepared by lithium metaborate fusion. Other elemental concentrations in solids were determined using perchloric acid solutions.

[e] "Less than" values indicate analytical detection limit.

[f] Concentrations in extracts measured by atomic absorption spectrophotometry.

[g] Not determined because boron and mercury are lost during digestion procedure.

TABLE E-4. CONCENTRATIONS OF MAJOR AND MINOR SPECIES IN RIVERSIDE SPRAY DRYER WASTE PRODUCTS (All concentrations are in weight percent)

	Low Sulfur	High Sulfur	High Sulfur with $CaCl_2$	NBS Standard Fly Ash No. 1633	
				Measured Concentration	Certified Concentration
SiO_2	21	15	17	47	45
Al_2O_3	10	6.2	6.6	23.6	24
TiO_2	0.5	0.4	0.4	1.23	1.20
Fe_2O_3	3.3	5.6	6.4	9.0	8.9
CaO	22	28	25	6.2	6.4
MgO	2.3	0.8	0.8	2.5	2.7
Na_2O	0.46	0.14	0.43	0.46	0.43
K_2O	0.95	1.0	1.1	1.9	2.1
SO_3	1.2	8.7	2.7	-	-
SO_2	8.5	18.4	20.1		
CO_2	2.2	2.7	2.7		
Cl	<0.1	<0.1	1.0		
H_2O^a	<0.1	4.6	1.0		
H_2O^b	0.4	0.5	1.1		
H_2O^c	0.4	3.3	1.0		
H_2O^c	1.3	2.8	3.0		
TOTALS	74.7	98.2	90.3	91.9	90.7

[a] Hydroxide reported as water.

[b] Water from moisture determination.

[c] Calculated water concentration assuming all sulfite in product is present as calcium sulfate dihydrate.

[d] Calculated water concentration assuming all sulfite is present as calcium sulfite hemihydrate.

APPENDIX F

JOY/NIRO COMMENTS

COMMENT I: Page 7-46. Last paragraph regarding residence times:

The designed spray dryer gas retention time for the Riverside system is 12 seconds. During the more than 3 years of testing and operation, the spray dryer has been operated at up to 125 per cent of the design gas flow rate resulting in gas residence times as low as 9 seconds. In no instances has this reduced residence time resulted in problems with moist product or deposits. The Riverside spray dryer consistently operates at residence times of 12 seconds or less.

On the basis of these results, JOY/NIRO disagree with the supposition presented in the report that 14 second residence time may have been the reason for successful operation during this test program.

COMMENT II: Page 3-4, Paragraph 2: Regarding Bag Life.

The Teflon B coated woven fiberglass material (9.3 oz./yd^2, texturized) was installed in the N.S.P. Riverside FGD baghouse in January, 1981 and has been subjected to various kinds of operating and testing conditions. To date, after more than four years in operation at Riverside, the material has shown a very low failure rate; and the failures were apparently limited to the mishandling during initial installation, or during maintenance and tests performed inside the compartments. The material evaluation indicates no pressure drop problem and no sign of strength deterioration. This fabric has subsequently been installed in the three full-scale commercial installations. At Basin Electric Antelope Valley Unit 1 and Sunflower Electric Holcomb station, it has been in service for nearly two years with virtually no bag failures.